LAKE AND RASTALL'S

TEXTBOOK OF GEOLOGY

REVISED BY

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PREFACE

When the fourth edition of this book was approaching exhaustion, Mr. Lake generously made over to me all his author's rights in future editions, in order to facilitate a complete revision of the work, which he himself did not wish to undertake. Consequently, although the original plan is unchanged, the whole has been carefully revised and to a large extent re-written. Special care has been taken to avoid the common error of making successive editions of a textbook more and more complicated, so that eventually the whole founders under a mass of unintelligible detail. In course of time parts of the subject have become of greater and others of less importance. Some sections have therefore been shortened in order to make room for new matter. A good deal of mineralogy and petrology, more properly belonging to an advanced stage of a geological course, has been eliminated, and the chapters dealing with Igneous Rocks and Metamorphism have been shortened and run into one. On the other hand, the parts dealing with Sedimentary Rocks have been expanded and modernised, in conformity with the great developments of that subject in recent years. In order to avoid some repetition the chapters on Marine Denudation and Marine Deposition have been combined and largely rewritten. In several parts of the book many new descriptive examples of geological phenomena have been introduced, largely based on my own observations in many parts of the world.

The Stratigraphical chapters have been in several instances somewhat simplified. The principal change is the treatment of the Permian and Trias in one chapter, under the title of New Red Sandstone, which is in fact a return to an earlier practice, in conformity with the recent trend of opinion in this country. The chapter on the Pleistocene has been kept as short as possible, since it is impossible in an elementary textbook to discuss the enormous amount of detail, largely in reality Prehistoric Archaeology, which now figures in the geological literature of this period.

In the revision of the Stratigraphical chapters the admirable handbooks published by H. M. Geological Survey, entitled *British Regional Geology*, have proved invaluable, and in controversial matters these have usually been accepted as the final court of appeal.

In the task of revision I have received much help and advice from several friends, to whom I offer my best thanks. I am specially indebted to Dr. J. E. Hemingway of Leeds University for assistance

with the Lower Carboniferous rocks of northern England, and to Mr. R. J. Hart, Scholar of Christ's College, Cambridge, who has re-written the sections on Palaeobotany throughout. Professor Trueman criticised the original chapter on the Coal Measures and suggested some emendations; Mr. H. G. Smith helped me to modernise the account of the London Basin; and Mr. J. Romanes has brought up to date his former contribution on the Geology of Petroleum.

It must be understood that Mr. Lake is in no way responsible for the new matter in the chapters originally written by him, or for any errors that may be found therein.

R. H. R.

CAMBRIDGE,
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A TEXTBOOK OF GEOLOGY

CHAPTER I

INTRODUCTORY

The literal meaning of the word *Geology* is 'the study of the earth,' but for practical purposes some limitation of this extremely wide scope is obviously necessary. It is, however, exceedingly difficult to draw up a working definition that is not open to innumerable logical objections: a certain amount of common sense has to be allowed. The general idea of the subject of geology entertained by most people is the study of rocks and fossils, and this, if interpreted in the widest sense, is by no means a bad definition. But geology must also be taken to include the historical aspect, the evolution of the earth as a whole and of its component parts, as revealed by this study. Furthermore, although it may at first sight appear somewhat paradoxical, the whole water system of the earth plays a foremost part. The definition of geology as the study of rocks and fossils also possesses another advantage in that it excludes the necessity of considering the state of the earth before there were any rocks, a subject which even now, or perhaps it would be better to say, now, more than ever before, is highly speculative. From this point of view, then, geology may be said to begin with the oldest rocks, and these contain no fossils. Hence, historically, the study of rocks, or petrology, comes before the study of fossils, or palaeontology, and in actual work it is most convenient as well as most logical to follow this order. Again, since rocks are composed of minerals, the science of mineralogy also comes in at an early stage. Strict definitions of minerals, rocks and fossils may be postponed for the present.

It is a fundamental doctrine of modern geology that the present is the key to the past. This principle of Uniformitarianism was enunciated about a hundred years ago by Sir Charles Lyell, in contrast to the theories of recurring catastrophes which had held sway up to that time. It is believed that the processes now going on, both on land and in the sea, are the same in kind, if not in degree, as those that prevailed in the older stages of geological history, and it is important to realise that there is no evidence for a continuous cooling of the earth as a whole throughout geological time. There have undoubtedly been variations of climate locally, as shown by the evidence for the

occurrence of ice-ages and periods of tropical climate at different times in the same place, but it is probable that from a very early time, the earliest time or nearly so of geological history as already defined, the average temperature of the earth's surface was much the same as it now is, and after the appearance of life on the earth this must almost necessarily have been so. And life is known to have existed a very long time ago. By various physical methods, as will be explained later, it has been found possible to estimate in years the actual age of the rocks, and it may be said that the figures thus obtained are very much larger than those formerly current.

Acting on Lyell's uniformity principle, we begin with the study of the earth as it exists to-day. This is called Physical Geology and is really very much like physical geography, except that more attention is paid in the former to internal structures as well as to external forms, but their methods are very similar and are constantly becoming more so. Physical geology finally combines its results with those of Petrology and Palaeontology to form Stratigraphy, which really amounts to the elucidation of the past history of the earth.

From the geological point of view the earth may be regarded as consisting of two concentric shells and a central sphere, of very different natures. As a matter of convenience the two shells may also be called spheres, though that is not strictly correct: the three components are then the atmosphere, the hydrosphere and the lithosphere. The atmosphere is a continuous layer of gases, surrounding the whole globe and of indefinite outward extension. The hydrosphere, which includes all the surface waters of the globe, differs from the others in being discontinuous; some parts of it, such as the inland seas and some lakes, being entirely disconnected from the rest. The third of these spheres, the lithosphere, is the solid earth, and it is essentially the province of geology to study its structures and history. As will appear later, much recent research has been devoted to the investigation of the deeper, inaccessible parts of the earth by various indirect methods, since they are not open to direct observation, and it has been found possible to draw conclusions indicating a further subdivision of the solid earth into shells and a nucleus of different constitutions, but for the present any consideration of these may be postponed and the lithosphere treated as a whole.

The three zones as above defined are very closely connected among themselves and there is a constant transference of material from one to the other. All water surfaces exposed to the air are continually undergoing evaporation, and thus the water is transferred from the hydrosphere to the atmosphere. The reverse process is also constantly in progress, as is shown by the fall of rain and snow and the deposition of dew. Water also exercises a solvent action on some of the con-

stituents of rocks, and the dissolved material passes from the lithosphere to the hydrosphere. Direct transfer between the atmosphere and the lithosphere is of subsidiary importance, but occurs in certain chemical reactions, and in connexion with volcanic phenomena. It would be easy to go on multiplying instances of this transfer of material between the different zones, but enough has been said to show that a close connexion exists between them.

The Atmosphere.—The atmosphere consists mainly of the mixture of gases called air but it always contains also more or less water in the form of vapour, and locally also in the liquid form, as clouds and rain or solid as snow and hail, as well as usually a small but very varying proportion of solid matter as dust, or in civilised countries as smoke. The air is a mixture in the chemical sense, not a definite compound, and its composition may vary, though actually this variation is confined within very narrow limits, fluctuations in the proportion of water-vapour being the most important. The amount of water that can be held in the air in the state of vapour is a function of the pressure and temperature, the last being by far the most important. This leads to the curious result that, as it is said, the clear air over the hottest part of the Sahara desert may actually contain more water-vapour than is present during a cold winter fog in England. But by far the most important constituents of air are oxygen and nitrogen, which form about 98·5 per cent. of the whole, while there is always a small proportion of carbon dioxide, and traces of ammonia and nitric acid. In the air of towns other substances are found in perceptible quantities, such as compounds of sulphur and many other gases, the products of combustion of coal and gas in domestic fires and innumerable industrial processes. During volcanic eruptions unusual gases are often evolved in enormous quantities and may cause considerable temporary variations in the composition of the air in their neighbourhood.

For our present purpose the atmosphere may be regarded as a mixture of oxygen, nitrogen, carbon dioxide and water-vapour, in approximately the following proportions:

	Per cent.
Nitrogen	77·91
Oxygen	20·66
Water-vapour	1·40
Carbon dioxide	·03
	100·00

The nitric acid and ammonia generally amount to about one part in a million.

The gas which was formerly regarded as pure nitrogen really contains small proportions of several others; helium, argon, neon, etc. These gases are all singularly inert, and enter into no chemical combinations.

They are, therefore, of no significance in geology, so far as is known, although some of them have important industrial applications.[1]

It has already been pointed out that the amount of water-vapour in the atmosphere is far from constant: a continual transference is taking place in this respect between the atmosphere and hydrosphere, in both directions. Water is continually being removed by evaporation into the atmosphere, and carried from place to place by air-currents. Sooner or later it is again condensed into the liquid or solid form and falls as rain or snow, and thus completes its cycle of transformation. This constant circulation of water between the two spheres is of enormous importance, since it constitutes the machinery of the most important of all geological agents, viz., running water. Rain falls on the land, and under the influence of gravity, obeying the ordinary laws of liquids, it tends to seek the lowest possible level, thus forming the great network of streams, rivers and lakes which covers the surface of the land, and also maintaining the ocean itself at a generally constant level.

The air does not remain at rest but is in a constant state of motion. When this motion is sufficiently active to be perceptible to our senses it is called wind, but besides this there is a constant imperceptible circulation in the air, and especially a rise of warm air and descent of cold air, by virtue of variations of density induced by changes of temperature. It is impossible here to enter upon a detailed consideration of the winds and the whole class of phenomena which may be summed up in the convenient if somewhat vague term, *Weather*. It must suffice to say that the most important factors in producing meteorological changes are variations of the pressure and temperature of the air. If the air in two adjoining areas is at different temperatures and under different pressures, there will be a transfer of matter from one to the other, tending to restore equilibrium, and the result will be wind. These air-currents or winds transfer water-vapour from one place to another, and under the influence of a fall of temperature this water forms rain or snow. Hence wind has an important geological action by virtue of its carrying powers. But wind also possesses a certain dynamical force of its own, and may act as an agent of destruction. In a great storm it is clear that much material is often moved from place to place. Great changes are often wrought in the face of the country by the power of the wind alone, and this work must have its own geological effect, either direct or indirect. Ordinary winds must also exert a similar influence in a less degree; and, indeed, the wind is a geological agent of no small importance.

The directions of the air-currents are not purely arbitrary but are governed by certain laws.

[1] The helium which has been used in America for filling airships is obtained from natural gas-wells, not from the atmosphere.

Primarily they are determined by variations of temperature and pressure in different parts of the earth's surface, and especially by the distribution of temperature-zones, parallel to the equator. If this were all, we should expect the heated air of the tropics to rise, while its place would be taken by a current of cold air flowing in from the direction of the poles, so that at the surface there would always be a wind from the north in the northern hemisphere and from the south in the southern hemisphere, while in the upper regions of the air the directions would be reversed. But the matter is complicated by other factors, and especially by the rotation of the earth on its axis, the irregular distribution of land and sea, and the diminution of the circumference towards the poles. Consequently the actual course pursued by these major air-currents is curved. In the northern hemisphere the direction of movement is counter-clockwise, in the southern hemisphere clockwise. Thus in the northern hemisphere the warm, damp winds from the tropics blow from the S.W., while the cold arctic current comes from the N.E. In the more open parts of the oceans these directions are maintained with a fair amount of regularity, especially those of the currents blowing towards the equator, which are known as the Trade Winds. But over the continental areas the conditions are too complex for any uniformity to be maintained. The direction of the winds is affected by the distribution of land and sea, by variations in the relief of the land and innumerable other local causes, so that the utmost irregularity prevails. This irregularity of the winds produces variations also in rainfall and temperature, and the sum of these variations may be expressed by the word *Climate.* Climate is very important geologically and produces marked effects, as will be shown in detail later on.

The extraordinary physical conditions in the upper atmosphere, revealed by high balloon ascents and the study of wireless waves, do not seem to have any geological significance, except in so far as they presumably play a part in keeping climatic conditions steady at lower levels. Even Mt. Everest, 29,000 feet or 8,880 metres high, does not quite reach the lower limit of the zone of constant minimum temperature (— 100° F.) which extends from 10 to 40 kilometres.

The Hydrosphere.—This includes the whole body of water existing as such on the surface of the globe and in the interstices of the lithosphere. It has been already pointed out that there is a constant interchange between this and the atmosphere, and as a result of numerous chemical processes there is also much interaction in this respect with the lithosphere. Processes of hydration and dehydration are continually going on, and water is constantly being absorbed or set free as a result of chemical actions. Many minerals and rocks also contain water, either absorbed or in combination, but with this part of the subject we are not now concerned. It is necessary now only to deal

with the visible water, which exists as such either in the liquid or the solid form.

Natural water is commonly regarded as of two kinds, fresh water and salt water, but this distinction is artificial and cannot be maintained. All waters contain a certain amount of saline matters in solution, and the difference is only one of degree. The waters of the sea and of certain lakes contain such a high proportion that it is perceptible to the taste, but in the case of many of these lakes it is clear that their excessive degree of saltness has been produced by concentration of the salts contained in so-called 'fresh' water; and the saltness of the sea is probably due to the same cause, viz., concentration of soluble material brought down from the land during innumerable ages.

There is at any rate one distinction between salt and fresh water important for our present purpose, and that distinction is biological. The inhabitants of salt and fresh water are markedly different, and this fact is of great geological importance.

For all practical purposes, then, the hydrosphere consists of two principal parts, the oceans and seas, and the water-system of the land. The former is continuous, since all its parts are in direct connexion; the latter is not, but consists of innumerable detached portions, scattered over the surface.

The oceans cover about 72 per cent. of the whole surface of the globe, or just over 143,000,000 square miles, but over a certain proportion of this area the water is comparatively shallow. Soundings show that in very many cases the submarine slopes surrounding the great land masses are very gradual down to a depth of about 100 fathoms, and then the gradient suddenly becomes much steeper. It has, therefore, come to be customary to regard the true boundary between the continental plateaus and the ocean basins as occurring at the 100-fathom line, rather than at sea-level. The area of this submerged part of the continents is about 10,000,000 square miles. After this adjustment, therefore, the total area of the ocean basins is about 133,000,000 square miles and that of the continents 64,000,000 square miles, or approximately in the proportion of two to one.

The floor of the oceans is by no means flat and uniform, but is diversified by hills, valleys and plains much like those of the land. The development of the method of echo-sounding, which enables great numbers of observations to be taken quickly and easily, has shown that this diversity is much greater than was formerly supposed, and it is inadvisable to make any dogmatic statements as to what the floor of the sea is really like until much more information is available. But at any rate this much may be safely said: that the maximum depths hitherto recorded are not very much greater than the heights of the highest mountains, namely 34,000 ft., as against the 29,000 ft. of Mt.

Everest, while it is quite possible that still larger figures will be recorded. It is a point of high geological significance, as will be explained later, that the greatest depths yet found are all in long narrow belts comparatively close to land. These *deeps* indicate that submarine slopes are often exceedingly steep, quite sufficiently so to allow of the sliding under gravity of great masses of marine floor-deposits, especially during earthquakes, and it is possible that in some places even the solid land is slipping down towards them. Many attempts have been made to compute the average depth of the oceans, which is probably somewhere between 2,000 and 3,000 fathoms, whereas the average height of the land is probably under 2,000 feet: hence sea-level is far from being the mean elevation of the surface of the lithosphere.

As in the atmosphere, so also in the seas there is constant movement going on, at any rate in the parts directly accessible to observation. It is probable that in the deeper parts of the great ocean basins this movement is very small indeed, but at and near the surface the water is in constant motion. This motion is of several kinds: there are the purely superficial movements of the waves, due chiefly to the wind; somewhat more deep-seated are the effects produced by variations of temperature, assisted to a considerable extent by wind action; this results in the production of currents. The direction of flow of these currents is greatly modified by the form and distribution of the land-masses, but on the whole it corresponds fairly well with the directions of air movement. The dominant feature of the whole is a flow of warm water from the equatorial regions towards the poles and a corresponding return flow of cold water towards the equator. These currents produce very important effects on climate, though perhaps less than was formerly believed; and in particular it appears that the influence of the Gulf Stream on the climate of Western Europe has been exaggerated. The warmth of this region is probably to be attributed to wind-currents rather than to sea-currents. The third great disturbing element in the waters of the ocean is the attraction of the sun and moon, especially the latter, on this great mass of mobile liquid, which gives rise to tides. This causes not only a rise and fall of level, but also produces well-marked currents, which differ from the class previously mentioned in being inconstant in force and direction. The geological and climatic effects of these movements of the water of the ocean are of great importance, as will be seen in later sections.

It has already been mentioned that sea-water contains a considerable amount of various soluble salts. This proportion is not constant, but is influenced by local causes. Thus in a partially enclosed area in a warm climate there is considerable loss by evaporation so that the solution tends to become more concentrated. For this reason the Mediterranean is more salt than the average. Again, if a large number of rivers flow into a partly enclosed basin, where evaporation is small,

the solution will become more dilute, and the water may even come to be merely brackish, as in the case of the Baltic and other inland seas. But these are merely local variations on a small scale and the composition of the waters of the open ocean is fairly constant.

According to the Reports of the *Challenger* expedition, 1,000 parts of water from the open ocean contain about 34·4 parts by weight of mineral matter, and the percentage composition of this dissolved matter is shown in the following table.

	Per cent.
Sodium chloride	77·758
Magnesium chloride	10·878
Magnesium sulphate	4·737
Calcium sulphate	3·600
Potassium sulphate	2·465
Magnesium bromide	·217
Calcium carbonate	·345
	100·000

It should be noted that the combination of acid and basic radicles into salts, as shown in this table, is purely arbitrary and a matter of convenience. Many if not all the compounds are no doubt dissociated in so dilute a solution.

It will thus be seen that by far the most abundant constituent is sodium, and salts of magnesium are also very abundant. Calcium occurs in less quantity; but the compounds of this element play a very important geological part, and in particular calcium carbonate is absolutely essential for building up the structures of a large proportion of the living inhabitants of the sea.

Besides this solid matter sea-water also contains dissolved gases. These gases are essentially the same as those of the atmosphere, but they occur in very different proportions. Since the solubility of gases in water is increased by pressure it follows that the amounts occurring in the deeper parts of the sea must be much greater than near the surface. It is unnecessary to enter into any details as to these dissolved gases, and it must suffice to say that the only ones of any practical importance are oxygen and carbon dioxide, which are closely concerned in the vital activity of animals and plants.

The Lithosphere.—Before we enter in detail into a consideration of geological processes and their results, it is necessary to have some preliminary acquaintance with the material on which they have to work. It is impossible rightly to understand the mode of action of any force unless we know the nature of the substances acted on, since the same agency may produce totally different results under different circumstances. In the first place, therefore, we shall give a brief and condensed account of the structure and composition of the most important features of the earth's crust, leaving full details for subse-

quent sections. This course may involve a certain amount of repetition, but this is probably unavoidable in any case.

The lithosphere must obviously contain all the terrestrial elements except the comparatively small number only known to us in atmospheric gases, but these elements occur in very different proportions. The majority of them, including the most valuable metals, are in reality very rare, and it is only a comparatively small number, not more than a dozen or so, that are really abundant. The following table, adapted from one compiled by F. W. Clarke, was obtained by the summation of an enormous number of analyses of rocks from all parts of the world and must come very near the true average composition of the part of the earth that is accessible to us.[1]

	Per cent.		Per cent.
SiO_2	59·08	H_2O	1·30
Al_2O_3	15·23	P_2O_5	0·28
Fe_2O_3	3·10	CO_2 and C	0·04
FeO	3·72	Cl	0·04
MgO	3·45	S	0·05
CaO	5·10	MnO	0·12
Na_2O	3·71		
K_2O	3·11		
TiO_2	1·03		99·36

The constituents are here given, not as elements, but in the form always used in the statement of rock analyses. It will be observed that the first ten items in the list make up nearly 99 per cent. of the total, while all the remaining elements only amount to about two-thirds of one per cent. of the whole accessible part of the earth.

The composition and physical condition of the inaccessible interior of the earth remains unknown. By various geophysical methods, especially by the study of earthquake records, it has been shown that the density of the earth does not increase regularly and continuously downwards, but that at certain levels there are changes of composition or physical state, especially sudden increases of density, that produce variations in the velocity of earthquake waves. There is, however, much difference of opinion as to the actual depth of these discontinuities, so that the figures here given should be taken as approximations, rather than as proved values. The outer cover of sedimentary rocks varies greatly in thickness and may even be absent in some parts of the world: it is estimated that it cannot average much more than 2 kilometres, though in places it may be as much as 20 kilometres thick. The next shell consists of crystalline rocks with high percentages of silica, alumina and alkalis and consequently of low density, averaging about 2·80 or a little less. As a useful abbreviation this is called the

[1] Clarke, F. W., *The Data of Geochemistry*, Bulletin 770, United States Geol. Survey, 5th edition, 1924, p. 34, where the full table will be found.

Sial, from the predominance of Si and Al. Under the great continents its thickness is believed to be of the order of 40 kilometres, though this is one of the most controversial figures, while in the Pacific region it may be absent altogether and under the Atlantic perhaps very thin, or absent in places. There is little or no doubt that below the Sial comes a thick shell of distinctly higher density (over 3) consisting largely of silicates of magnesium and iron, and therefore called the *Sima*, having the general composition of the lavas of so many oceanic volcanic islands. The downward extension of the Sima is unknown and everything beyond is highly speculative. But earthquake observations show two further well-marked discontinuities at about 1,200 and 2,900 kilometres from the surface. Goldschmidt has suggested that silicates extend down to the first-named : then comes a shell of sulphides and oxides of the heavy metals, with a central core of nickel-iron. At any rate, as the density of the earth as a whole is nearly double that of the surface rocks, the interior must be made of something very heavy and by analogy with meteorites, nickel-iron is a plausible guess.

The Lithosphere or solid part of the earth, so far as it is open to our inspection, consists of *rocks*, and it is necessary to understand clearly what is meant by this term. A rock may be defined as *an aggregate of mineral particles*, without any reference to its state of cohesion. As usually understood the term conveys an idea of hardness, but this is unessential. To the geologist, loose sand or soft plastic clay are rocks just as much as the hardest granite, and the hardness is often a secondary or superinduced character.

As will be seen from the above definition, before we can proceed to the consideration of the rocks as such it is necessary to have some acquaintance with the minerals of which they are composed. Minerals are substances having a definite crystalline form and a more or less definite chemical composition, and the number known to exist is very great. The majority of these, however, are of small geological importance, and their detailed study must be relegated to the science of Mineralogy. Fortunately it so happens that the number of minerals that play an important part as rock-formers is limited, and it is possible to draw up a short list which will suffice for our present needs. In later chapters the subject of the mineralogical and chemical composition of rocks will receive fuller treatment.

Common Rock-forming Minerals.—The great bulk of the rocks forming the accessible portion of the globe consist of the minerals included in the following list, associated in very variable proportions. Some rocks are homogeneous, consisting of one mineral species only, but most are heterogeneous, containing two or more.

It will be observed that some of these are group-names, that is, general terms comprising several closely allied species which are separated by the systematic mineralogist. However, this separation

List of Common Rock-forming Minerals.

Quartz.	Pyrite.
Felspar group.	Calcite.
Mica group.	Dolomite.
Amphibole group.	Rock Salt.
Pyroxene group.	Gypsum.
Olivine.	Apatite.
Magnetite.	Garnet.

can often only be made by refined methods, and for our present purpose these minute differences are unimportant, since the physical and chemical properties of the members of each group are very similar.

It must be clearly understood that the above list includes only a few of the commonly occurring minerals and might be very largely extended, but it is fairly representative and the student is recommended to make himself familiar with their chemical and physical characters, both by study of actual specimens and by the perusal of a small text-book of mineralogy.[1]

Different Classes of Rocks.—As we have already seen a rock may be defined as an aggregate of mineral particles; but these aggregations are not all formed in the same way. Broadly speaking the rocks constituting the earth's crust may be divided into two great groups, the *igneous* and the *sedimentary* rocks. These two groups differ fundamentally in their mode of formation, since the igneous rocks are formed by consolidation from a state of fusion, while the sedimentary rocks are built up of the remains of pre-existing rocks, or else are deposited from solution by chemical or organic agencies. Corresponding to these differences of origin the whole structure and mode of occurrence of the two classes are essentially different, and it will be necessary to consider each class separately.

Intermediate in some respects between these two great divisions is the group of rocks known as *Pyroclastic.* These consist of igneous material, but have been formed in a manner more analogous to the sediments. They include the volcanic ashes and tuffs, and their consideration may be postponed till we come to consider the phenomena of vulcanicity in detail. Some writers make a fourth great class for the *Metamorphic* rocks, or those which have undergone such great alteration through heat or pressure, or both combined, that their original character is lost. However, these rocks were originally either igneous or sedimentary, and so the distinction is artificial.

The Igneous Rocks.—The igneous rocks as at present existing occur in two distinct forms, the extrusive or volcanic rocks, which have broken right through the crust and have been poured out at the surface

[1] A very useful book for the purpose is *Rutley's Elements of Mineralogy*, revised by H. H. Read, 23rd edition. London, Murby, 1936.

as lava-flows from volcanoes, and the intrusive rocks, which have been injected into the crust, without reaching the surface. These two classes differ in form and structure, but have a common origin.

The forms assumed by extrusions of lava depend entirely on the laws governing the flow of liquids, and the chief factor in the case is the degree of viscosity in the molten lava at the time of extrusion; obviously a mobile liquid will flow further and spread itself out in a thinner sheet than a viscous one, other things being equal. Lava-flows therefore take the form of a sheet of greater or less extent, resting on what was then the surface of the ground, and all overlying rock must be newer in date. When a lava-flow occurs in this way in the middle of a succession of sedimentary rocks it is said to be interbedded with them, and is spoken of as a *contemporaneous* volcanic rock.

On the other hand, the intrusive rocks have been injected into or between rock-masses already in existence, and the forms assumed by intrusions are capable of much greater variety than those of lava-flows. On the whole they are determined by the position of the planes of least

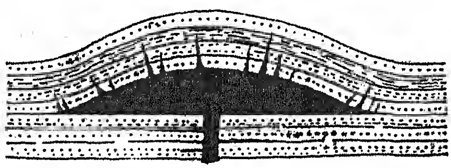


FIG. 1.—LACCOLITH.

resistance. Since they are often injected into sedimentary rocks their form depends on the structures of the latter.

The most common forms assumed by intrusions are *Stocks*, *Laccoliths*, *Bathyliths*, *Sheets* or *Sills*, *Dykes*, and *Necks*.

Stocks are large masses of rock, often many miles in diameter, which appear to break through the strata without much reference to their structure and arrangement; they have steeply plunging contacts and no visible base.

Laccoliths are intrusive masses which have arched up the overlying strata in the form of a dome, and they have usually something of the form of a bun or flat cake (Fig. 1). Laccoliths are not well developed in Britain, but are very well seen in some of the western States of America.

Sheets or *Sills* are intrusions which have forced their way along the stratification planes of sedimentary rocks, so that they lie parallel to the strata, and therefore might be mistaken for contemporaneous lava-flows (Fig. 2). They can, however, be distinguished by the fact that the overlying as well as the underlying rocks are altered or 'metamorphosed' by the heat of the intrusion; and a sill does not necessarily keep to the same stratification plane throughout its whole extent, but

may cut across the strata, from one horizon to another. This is called *transgression*. One of the best examples of such a sheet in Britain is the Great Whin Sill of the northern counties of England, which is intrusive into the Carboniferous rocks over an area of several thousand square miles, and is on the average about 100 feet thick, and transgresses for several hundreds of feet.

The term *bathylith* or batholith is used to describe masses of igneous rock on an enormous scale and often originating at great depths. At the surface they are sometimes measurable by hundreds of miles, such as the great Coast Bathylith of British Columbia, which is 1,200 miles long and 150 wide, and of unknown extension underground in both length and width. Bathyliths are sometimes intruded along the axis of a major upward fold in the earth's crust. The best example of this in the British Isles is the great mass of granite that extends some 70 miles to the south-west from the neighbourhood of Dublin. It is now believed that many of the largest and deepest masses of igneous rock, where there is little or no evidence of the uplift of a cover, are due largely, if not entirely, to fusion in place and recrystallisation of already existing rocks, sometimes sediments, rather than to actual injection of liquid material. Otherwise, when there is no lift of the cover, it is extremely difficult to see where the material that originally occupied the space went to. This subject will be discussed again in a later chapter.

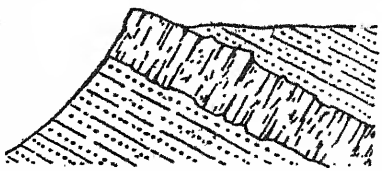


FIG. 2.—INTRUSIVE SILL.

Bathyliths may have an irregular upper surface, with projections or domes, called *cupolas* in America, such being often the seat of important ore-deposits. It is probable that the masses of granite in Cornwall are of this nature, only the cupolas being exposed. Sometimes when erosion has gone deeper isolated patches of the cover rock are left on the surface: if these extend downwards more or less in wedge form they are called *roof pendants*.

Dykes are vertical or highly inclined cracks in the crust which have been filled by an injection of igneous rock; they differ from sills in being as a rule more or less at right angles to the stratification, instead of parallel to it. Since igneous rocks are generally harder than the sedimentary rocks, dykes frequently stand up above the surface like walls, when the surrounding strata have been destroyed by weathering, and to this fact they owe their name. Dykes are very abundant in almost all parts of the world, and some very large ones exist in the north of England and the south of Scotland.

Closely allied to dykes are the smaller masses of igneous rock best described as veins. Their form is usually very similar to that of dykes,

but more irregular, and they have no necessary relation to planes of stratification.

The term *vein* is also used to describe similar structures not of igneous origin, or not directly so. Very often fissures of more or less regular form, traversing rocks in any direction, are filled or partially filled by crystalline minerals, quartz and calcite being by far the commonest.

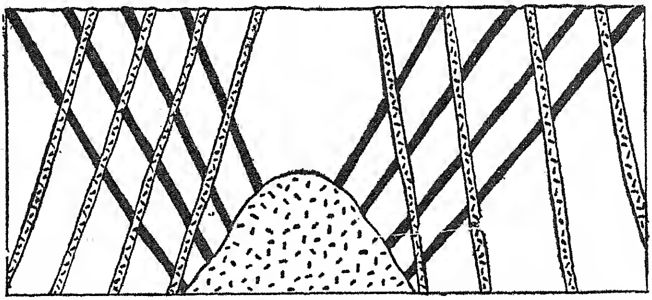


FIG. 3.—CONE-SHEETS AND RING-DYKES SURROUNDING A DEEPLY BURIED BOSS.

Many of these have been deposited from solution in meteoric waters at the ordinary temperature, though some quartz-veins are certainly of igneous origin. The use of the term *vein* in connection with ore-deposits is discussed in Chapter XIII.

Cone Sheets and *Ring Dykes*.—These special types of intrusion, which are closely related and occur together, have so far only been clearly observed in the British Isles, especially in Skye, Ardnamurchan and Mull. They can be most easily explained by means of a diagram. Both are nearly circular in plan, cone-sheets dipping inwards, often at about 45°, towards a centre, so that a set of them are like a series of inverted cones. Ring dykes, on the other hand, are vertical or dip very steeply outwards. Both types are considered to be due to the filling of cracks produced by strains set up by the uprise of a plug of molten rock deep below.

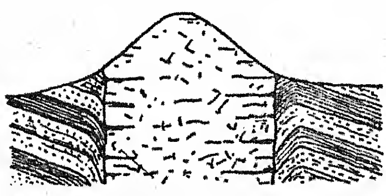


FIG. 4.—VOLCANIC NECK, FILLED WITH IGNEOUS ROCK.

Volcanic Necks.—In many ancient volcanic regions we find masses of igneous rock of a more or less circular cross-section and therefore somewhat cylindrical in form (Fig. 4). These often break through the surrounding strata quite regardless of the structure and arrangement of the latter. They are masses of solidified lava filling up the pipes or vents of ancient volcanoes, and are often spoken of as *necks*.

Besides the foregoing there are masses of igneous rock of quite

irregular forms which cannot strictly be referred to any of the above types. The forms of intrusions depend to a very large extent upon the structure of the rocks into which they have been injected, and these we must now proceed to consider.

The Sedimentary Rocks.—Since the sediments as a rule consist of particles which have been arranged under the influence of gravity, combined with water action, they frequently tend to occur in horizontal layers, often of wide extent. But since conditions are never uniform over the whole earth, or even over any considerable part of it, the lateral extension of a mass of sediment of any given composition must necessarily be limited. The result of this is that the thickness of the sediments laid down during a given time varies from place to place. A mass of material having a uniform composition throughout is called a *bed*, and from the above considerations it appears that all such beds must really be lenticular in form, though these lenticles are often of enormous extent compared to their thickness.

It is convenient to use the term *strata* when speaking in general terms of the sedimentary rocks, which compose the greater part of the visible crust of the earth, and it is the province of the stratigraphical geologist to study the nature and order of succession of the varying layers or beds composing these strata.

The character of the deposits formed naturally varies according to the prevailing conditions, and from a study of the nature of the sediments of any particular area we are able to draw conclusions as to the physical history of past ages in that area. It is unnecessary at present to enter into any details as to the minute structure of the sedimentary rocks, as this subject will be dealt with in a later chapter, but one or two examples may be given to show the relation between structure and origin. Suppose we find a rock consisting of a mass of well-rounded pebbles cemented together, in fact a consolidated gravel, it is obvious that at the time of its deposition the area was occupied either by a sea-beach or the bed of a river or lake, and so must have been either a land-surface, or close to a coast-line; similarly, a very fine-grained deposit containing only remains of marine animals indicates deep sea, and a thick bed of rock salt must have been formed by the drying up of a lake or inland sea. Thus by a study of the character and distribution of the sediments we are enabled to reconstruct the physical geography of the past.

Rock-structures.—The material of the sedimentary rocks is at first in a loose and incoherent condition, in the form of sand, mud, and so on. This applies to the deposits which are formed of material carried down from the land by water, and deposited in the sea or in lakes and rivers, and also to such accumulations as desert sands, but exceptions occur in the case of some accumulations formed by chemical agencies, or by the vital activity of animals or plants. For the present, however,

these exceptions may be disregarded, since the originally incoherent deposits form the majority. In course of time they lose this character, and become consolidated into hard masses, or *rocks* in the popular sense of the term. During these processes of consolidation various structures are impressed on the rocks, and these we must now proceed to consider briefly. Besides these original structures there are also structures of secondary origin, brought about by outside agencies after, and often long after, the original consolidation. Some of these structures are peculiar to the sediments, while others are common to both great classes of rocks, as will be pointed out in due course.

Stratification and Lamination.—If we examine any exposure of sedimentary rocks, on a sufficiently large scale, we shall see that the rock is not uniform from top to bottom, but is commonly marked out into bands or layers of varying appearance. These layers or *beds* are rendered visible by variations in physical character, such as differences of colour, hardness, and the like, and these usually indicate variations in composition. This well-known feature of sedimentary rocks is expressed by the general term *stratification.* Since the rocks are usually laid down over fairly wide surfaces, these beds are at first horizontal; as a result of disturbing forces of later date they often lose their horizontality, and become inclined at various angles or even bent into folds. Nevertheless the original stratification still exists.

When a considerable thickness of sediment has been piled up, the lower layers are naturally subjected to pressure produced by the weight of the overlying mass, and the simplest effect of this pressure is to bring about consolidation of the lower part. This can be clearly seen in the case of the muddy sediments of the moderately deep sea. Among the older rocks we are able to trace every gradation from soft mud, through clays of varying degrees of plasticity, up to a hard rock showing no definite structure, called a mudstone. This change seems to depend to a great extent on loss of water, since a very similar change can be brought about by slow drying of a clay by artificial means. It will be seen later on that drying is probably an important factor in producing rock-structures.

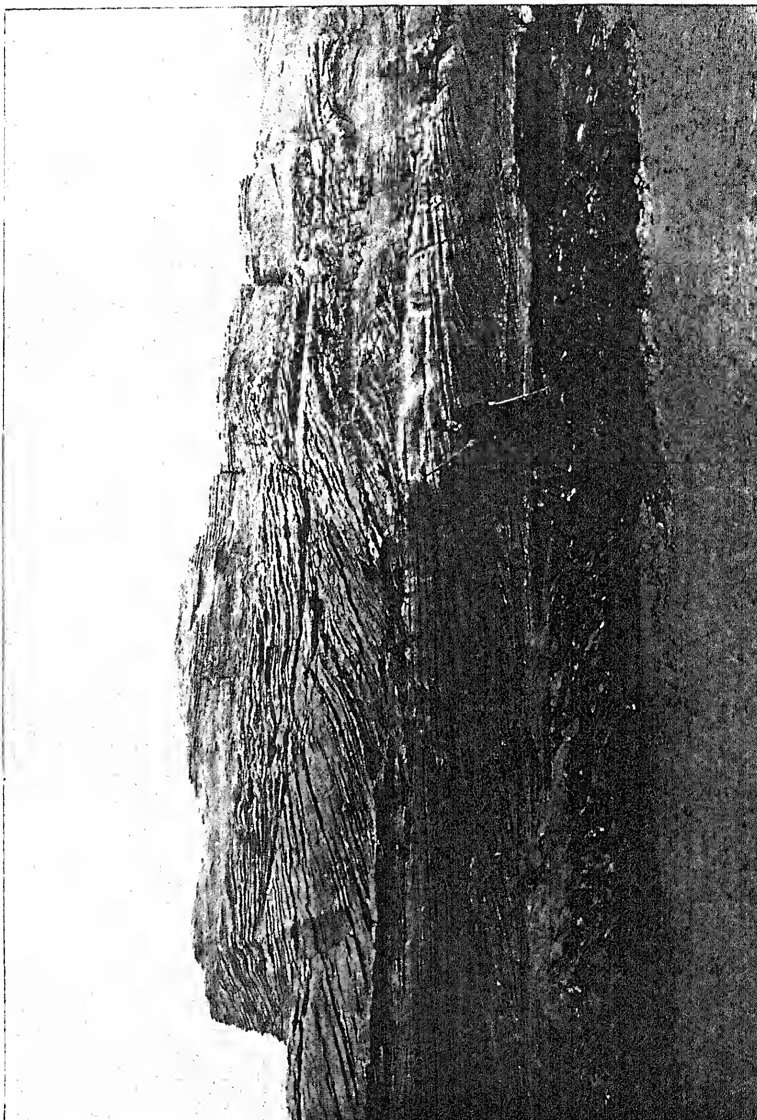
If such an originally homogeneous rock undergoes still greater pressures there will take place compression and rearrangement of particles. Rock particles are rarely of equal dimensions in all directions, and when subjected to pressure they tend to arrange themselves with their long axes perpendicular to the direction of pressure. In the case we are now considering this direction is vertical, since the force at work is the weight of the overlying strata. Consequently the longer axes of the particles lie in a horizontal position. If the rock was originally made up of flattened particles they will assume this position from the first. A rock built up in this way of particles all lying in one direction will split more easily in this direction than in any other, so that it

PLATE I

Photo by H.M. Geological Survey.

BEDDING: ALTERNATING THIN BANDS OF LIMESTONE AND SLATE, UPPER DEVONIAN. PADSTOW, CORNWALL.

PLATE II



C. A. Defieux, photo.

FALSE BEDDING IN TRIASSIC SANDSTONE, CHESHIRE.

will tend to split into layers parallel to the original bedding. This is known as *lamination*, and the thin layers are called laminae. A muddy sediment possessing this structure gives rise to the easily fissile rock known as *shale*.

In many of the finer-grained sediments mica is a very abundant constituent. As this mineral is always in the form of thin flat flakes it is very effective in producing lamination. It is also common to find rocks composed of alternating sandy and micaceous layers: these can be split easily into flat slabs and are called *flags*.

Lamination may also be brought about by pauses in deposition. Let us consider the case of a mud-flat between tide-marks. During high tide a layer of mud or river silt may be deposited over it: when the tide ebbs, the surface is exposed to the drying effects of sun and wind, and becomes somewhat hardened on the surface: the next tide brings a fresh supply of mud, and so on. Thus a deposit is piled up consisting of successive layers with a slight want of coherence between them, and this also gives rise to planes of easy separation or lamination.

It will thus be seen that the difference between stratification and lamination is one of degree rather than of kind. *Stratification* or *bedding* (Plate I) is the division of the strata into larger bands of varying character, conspicuous from a distance; while lamination is a splitting up into thinner layers, only visible on close inspection. However, in geological writings the term 'bedding' is often used in a rather vague way to indicate the occurrence of evident stratification on almost any scale.

Current-bedding.—This is a peculiar type of structure very characteristic of sandy rocks, and especially of those formed in shallow water under the influence of strong currents. In this case the beds are not horizontal and continuous over large areas, but often steeply inclined in various directions within a small space (Plate II) Consequently examination of a small surface often seems to indicate highly inclined strata, while the bedding of the whole is really horizontal on a large scale, as will be seen if we regard only the top and the bottom of the bed. A similar appearance is also often presented by masses of sand that have been transported by wind (sand-dunes), the differing degrees of inclination and directions of the stratification being due to winds of varying strength and direction.

Conformable and Unconformable Strata.—A series of beds following one another uninterruptedly in sequence, without any change in their general parallel arrangement, is said to be *conformable* (Fig. 5). In some districts great thicknesses of strata occur, often for several thousand feet, without any break. This indicates the prevalence of similar conditions for a long space of time, so that deposition of sediments has gone on uninterruptedly. Such strata have often been moved from their original position, uplifted and inclined, without their

conformability being affected. Suppose, however, that a set of marine sediments has been uplifted to form dry land; they are brought within

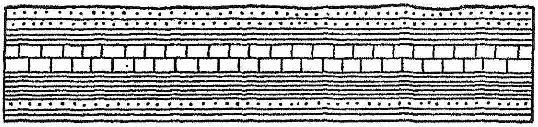


FIG. 5.—HORIZONTAL STRATA IN CONFORMABLE SERIES.

the reach of the agents of destruction and undergo *denudation* (Fig. 6). If these denuded strata are again brought below sea-level a fresh series of sediments will be laid down on the top of them. This second series

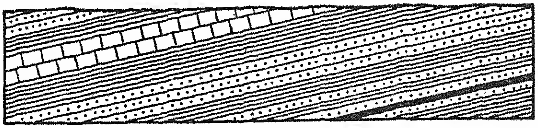


FIG. 6.—INCLINED STRATA IN CONFORMABLE SERIES.

will not necessarily be parallel to the first, and in any case there will be a gap in the succession. If the first series has been inclined as well as uplifted, the second set will rest on its worn and denuded edges,

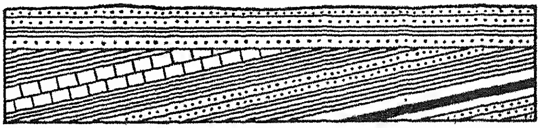


FIG. 7.—UNCONFORMITY.

and the bedding of the two sets will lie at different angles. This phenomenon is known as *unconformability*, and the two sets of strata are said to be *unconformable* (Fig. 7 and Plate III (i)). Since the sedimentary rocks are as a rule laid down in more or less basin-shaped areas, with gently sloping sides, such as lakes or the sea, it is evident that each successive bed will extend further in a horizontal direction than the one below it. This is called *overlap* (Fig. 8).

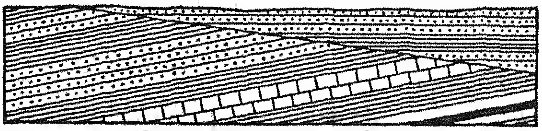


FIG. 8.—UNCONFORMITY WITH OVERLAP.

This type of structure is naturally very common, since every time the land sinks (or the sea rises) the area of marine deposit must necessarily extend gradually over the land, which nearly always slopes towards the sea. Numerous examples will appear in the chapters on stratigraphy.

It is by no means rare for deposition in any particular area to cease for a time, owing, for example, to a failure in the supply of sediment or a change in the direction of currents, without actual disturbance of the area itself: later, deposition may be resumed without any visible discontinuity. If the rocks contain fossils it is often possible to show that a certain period of time is unrepresented in the succession. This state of affairs, called a *non-sequence*, can obviously only be detected by comparison with other areas where the succession is complete.

Dip and Strike.—When a bed is inclined its surface makes a certain angle with the horizontal plane, and this angle is called the *dip* of the bed. It is measured in degrees from the horizontal, and the direction

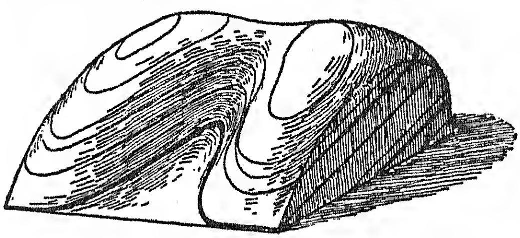


FIG. 9.—BEDS DIPPING AT A LESSER ANGLE THAN THE SLOPE OF THE VALLEY FLOOR; V OUTCROPS UP-STREAM.

of the dip is referred to the points of the compass. Thus the surface of a certain bed might be inclined downwards towards the north-east, and the greatest angle which could be measured between its surface and the horizontal plane might be 35°. This is expressed by saying that the bed dips north-east at 35°. The angle of slope measured in any other direction would obviously be less than the true dip. Thus it appears that dip may be described as the greatest angle made with the horizontal plane by a line lying in the bedding plane. This would be the course pursued by a drop of water running freely down the surface of the bed, since it is the steepest possible slope, and therefore the line of least resistance.

A horizontal line at right angles to the direction of dip is called the *Strike*. Thus, in the case before supposed, the strike of the beds would run north-west and south-east.

As the dip changes in direction so also the strike changes, and since by definition the strike-line is horizontal, it may also be regarded as a contour-line. In economic work and especially in oil-geology, great

use is made of the conception of underground contours at definite intervals in one selected bed as a method of representing the geological structure of an area, as distinguished from the surface topography.

If we imagine a piece of absolutely level ground composed of a series of inclined strata, the surface of the ground will consist of the truncated edges of the beds. The space occupied on the ground by any bed is called its *outcrop*, and the direction and width of this outcrop will evidently depend primarily on the dip. If the beds are horizontal the ground will be composed of the upper surface of the uppermost bed only, and the width of the outcrop is infinite. If the beds are vertical

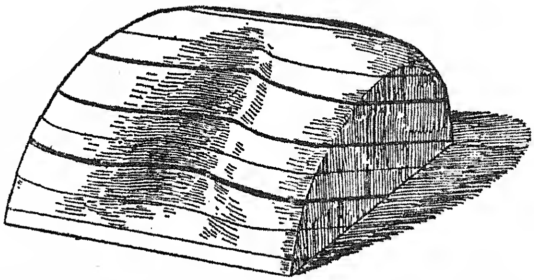


FIG. 10.—BEDS DIPPING AGAINST THE SLOPE OF THE VALLEY; V OUTCROPS UP-STREAM.

the width of the outcrop is the true thickness of the bed; in any intermediate position the width will depend upon the angle of inclination, i.e. the dip. Thus the outcrop of uniformly dipping beds on level ground will be a series of parallel bands of varying width. Here the strike and the outcrop obviously coincide.

If, however, the ground surface is undulating the matter is less simple. Vertical beds must in all cases crop out as straight lines, but inclined beds cannot do so. Their outcrops will follow sinuous courses, and the less the angle of dip the more sinuous their course will be (Figs. 9, 10, and 11). Finally, if the beds are horizontal, their outcrops will be parallel to the contour-lines, that is, the lines indicating equal heights above sea-level. This subject of dip, strike and outcrop is of the utmost importance in geological mapping, but cannot here be pursued further; for full details reference must be made to some special treatise or text-book of Field Geology.[1]

A very brief reference may, however, be made here to one or two points of importance that frequently crop up even in the most elementary discussions of field geology. It is obvious that if dip and strike remain uniform for a long distance, the outcrop of a particular set of strata may be of indefinite extent, but in practice it always ends some-

[1] A. Harker, *Notes on Geological Map-Reading*, Cambridge, 1926; G. L. Elles, *The Study of Geological Maps*, Cambridge, 1921.

where. The importance of a coast-line as a geological boundary is obvious. Further, it is clear that if an unconformity comes to the surface, the strata on the two sides of it will be different. If the forms of the land surface are such that a patch of older strata is exposed, at the bottom of a valley, surrounded by newer rocks, this is called an *inlier*, while, on the other hand, an isolated patch of rock left on the top of a hill is called an *outlier*. As will appear later, similar effects can also be produced by various types of disturbance of the earth's crust by folding and faulting. All these are dealt with in treatises on geological maps.

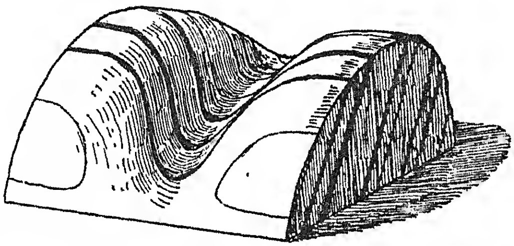


Fig. 11.—Beds dipping down the Valley at a Greater Angle than the Valley Slope; V Outcrops down-stream.
[Figs. 9, 10, 11 are drawn from Sopwith's models.]

Divisional Planes, Joints.—So far we have spoken of rocks as if they were continuous structures, forming one solid mass of indefinite extent, but this is not the case. Rocks are affected by planes of division of various kinds, which break them up into more or less well-defined masses. A brief reference has indeed been made to stratification and lamination, which are to some extent divisional planes, but frequently without actual discontinuity. In very many cases, however, we find that a rock-bed consists of separate blocks, often with considerable spaces between them. These planes of division are known as *joints* (Plate III (ii)). It is to be noted that joints are found in the igneous as well as in the sedimentary rocks. Their origin in both classes appears to be very much the same. Most commonly, perhaps, they arise from shrinkage after formation: in the igneous rocks during cooling, and in the sediments during drying. In other cases joints are due to strains set up by movements of the crust, as will be noticed further on. A good example of jointing in igneous rocks is afforded by the well-known columnar structure of the basaltic lavas of the Giant's Causeway and Fingal's Cave. A much less perfect system of joints is almost universal in igneous rocks, and there is a general tendency to split up into hexagonal columns or cuboidal forms. Jointing may be seen in almost any quarry, and it will often be noticed that the principal joints have a tendency to arrange themselves in two or three sets, more or less at

right angles. In sedimentary rocks one set is usually along the bedding planes, while the other two are usually parallel to the dip and strike respectively. These are called dip-joints and strike-joints. The smaller joints are often more irregular in their distribution. In chalk-pits in Cambridgeshire and elsewhere it can often be seen that the rock is divided up into irregular blocks by peculiar curved joints, and there is often evidence of differential movement along them. The origin of these curved joints is somewhat doubtful.

When differential movement has occurred along divisional planes of any kind in rocks, the sides of the fissure are often marked by fine striations or flutings, called *slickensides*. In fault-planes, where these are very common, they are often useful as indicators of the actual direction of the relative movement of the two sides.

Folding.—We have seen that the bedding planes of the stratified rocks do not always remain in their original horizontal position. As a result of the various movements of the earth's crust, to be hereafter described, they become inclined in various directions and at various

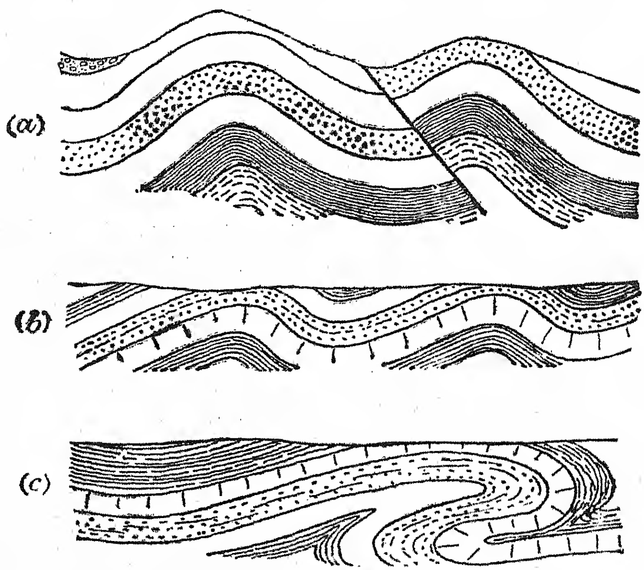
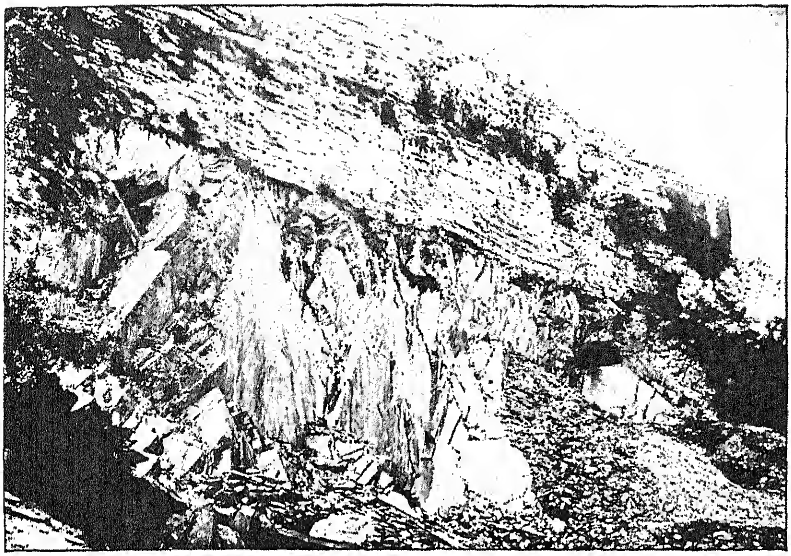


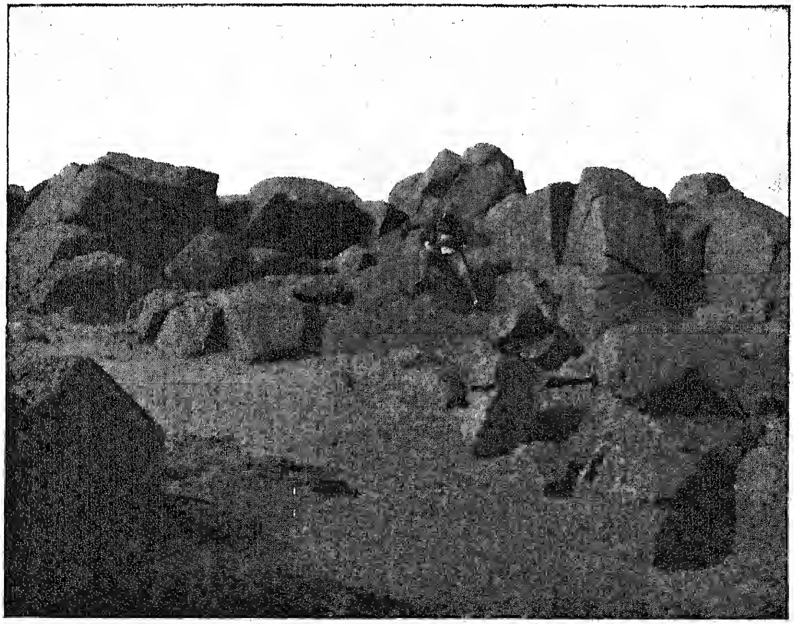
FIG. 12.—TYPES OF FOLDING.
a, Symmetrical folds; *b*, Asymmetrical fold; *c*, Recumbent fold.

angles (cp. Plate VI (ii)) But besides this simple tilting movement they often undergo bending or warping: this process is conveniently described as *folding*. A special nomenclature is in use to describe the different types of *folds* which may be produced, and the different parts of an individual fold. The simplest case is when the strata are simply



S. H. Reynolds, photo.

(I) CARBONIFEROUS LIMESTONE RESTING UNCONFORMABLY ON LUDLOW SLATES, NEAR SETTLE, YORKSHIRE.



R. H. Rastall, photo.

(II) JOINTS IN IGNEOUS ROCK. LITTLE KNOTT, CUMBERLAND.

PLATE IV

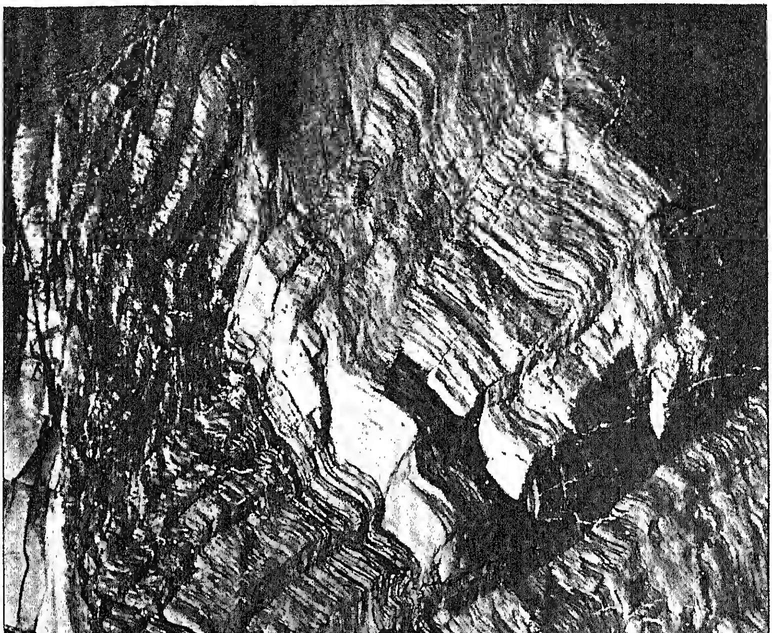


Photo by H.M. Geological Survey.

PUCKERED SLATE, SHOWING STRAIN-SLIP CLEAVAGE : THE TRUE CLEAVAGE IS NOT RECOGNISABLE.
WATERGATE BAY, CORNWALL.

lifted up in the form of an arch; this is called an *anticline*, and the beds dip on both sides away from the central line, the *axis* of the fold. The corresponding structure when the beds dip towards the axis is a *syncline*. *a*, Fig. 12 shows a series of beds folded into a succession of anticlines and synclines. In this case the slopes are similar on both sides of the axis, and the folds are said to be *symmetrical*. Since, however, folds are most commonly the result of a thrusting movement of the crust, acting in a tangential direction, one side of the fold is usually steeper than the other, as shown at *b*, Fig. 12. Such a fold is said to be *asymmetrical* (cp. Plate VII (i)).

The various parts composing such a wave-like fold are designated *limbs*, and three regions are usually distinguished, viz. arch limb, trough limb, and middle limb or septum, as indicated in Fig. 13. Folds of the type so far described are *normal*. But if the lateral thrust is still more powerful, the fold may be more or less overturned on the side away from the stronger pressure, forming what is known as an *overfold* (see *c*, Fig. 12). In this case it is evident that a vertical shaft sunk from the surface may pass through the same bed three times, and in one part of the shaft the succession will occur in reverse order, that is to say the beds in the middle limb are *inverted*. Such inversions are very common in many mountainous regions, which are usually built up of a complex series of folds.

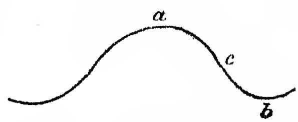


FIG. 13.—SYMMETRICAL FOLD.
a, Arch limb; *b*, Trough Limb; *c*, Middle limb, or septum.

If the elevation takes place around a point, so that the beds dip away from the centre in all directions, the resulting structure is called a *dome*; while if the dips are all inwards towards a centre, it is a *basin*. Domes and basins are not usually circular, but oval, and may be regarded as very short anticlines and synclines. It is to be noted also that folds are never of indefinite length, but eventually die out, so that in one sense they are only very elongated domes and basins. The difference is therefore only one of degree.

So far we have tacitly assumed that the axes of folding are horizontal, but this is by no means always the case. The axes are frequently inclined, and are then said to *pitch*. A fold whose axis was inclined downwards towards the S.E. would be said to pitch to the S.E., and the angle of pitch could be expressed in degrees, as in the case of dip.

One of the simplest cases of folding is the type known as *monoclinal*. This is often represented as a simple elevation or depression of one part of a region in relation to the other, with a curved portion between them; but it is doubtful if such a structure really exists. Monoclinal folds are in nearly all cases very asymmetrical anticlines with much

elongated arch and trough limbs and a very short, steep septum. Unfortunately, the term monocline is also used by American authors to describe a series of inclined beds all dipping in the same direction like Fig. 6.

By some authors the term *recumbent anticline* is used to describe an overfold. A series of overfolds arranged in such a manner that both limbs dip in the same direction is called *isoclinal* folding. Consideration of more complex arrangements of folds may be deferred till we come to treat of earth-movements in general, as they are most conveniently illustrated by the study of special examples.

Faulting.—Rocks do not possess much elasticity, and under the influence of the strains set up by crust-movements fractures are frequently produced. These fractures are known as *faults*. Thus it will be seen that faulting is closely connected with folding. The tension of the strata during folding frequently passes the limit of elasticity, and the rocks break along the line of least resistance. As a result of this fracture there will occur more or less differential movement of the rocks on the two sides of the fissure, and the amount of relative displacement may be measured. The fault-fissure may be either vertical or inclined: if inclined, the amount of inclination measured from the vertical is called the *hade* of the fault, and it is expressed in degrees.[1] The amount of

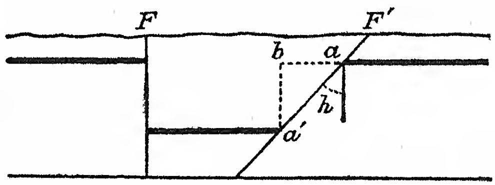


Fig. 14.—Diagram of Faults.
F, Vertical fault; *F′*, Normal fault; *baa′*, the dip; *h*, the hade; *ab*, the heave; *a′b*, the throw.

vertical displacement is the *throw* of the fault, and the side which is relatively raised is called the *upthrow* side; the other is the *downthrow* side. These relations are indicated in the diagram (Fig. 14). It is evidently immaterial in this case whether the strata on the right have moved up, or those on the left down: we are only concerned with relative displacement.

In dealing with inclined faults, however, there is one important distinction to be observed: at *b*, Fig. 15 is shown a fault inclined to the left; the downthrow also is to the left. This is called a *normal fault*. *c*, Fig. 15, shows a fault dipping in the same direction, while the upthrow is to the left, so that one part of the bed lies vertically above the other

[1] In economic work it is now more common to speak of the *dip* of a fault, similar to the dip of a bed. If d is the dip and h the hade, obviously $d = 90° - h$.

parr for a certain distance. This is called a *reversed fault.* Obviously, in the case of a reversed fault a vertical shaft sunk between certain points will pass through the same bed twice, while in a normal fault it cannot do so, and may even miss it entirely. In coal-mining districts the area within which a seam can be missed by a vertical sinking is often called a *want,* as the seam is wanting there.

It is obvious that a fault cannot extend to an indefinite length, but must end somewhere and somehow. Sometimes a fault ends against another fault, without any apparent continuation on the other side, but more commonly it just fades out: this means that the downthrow

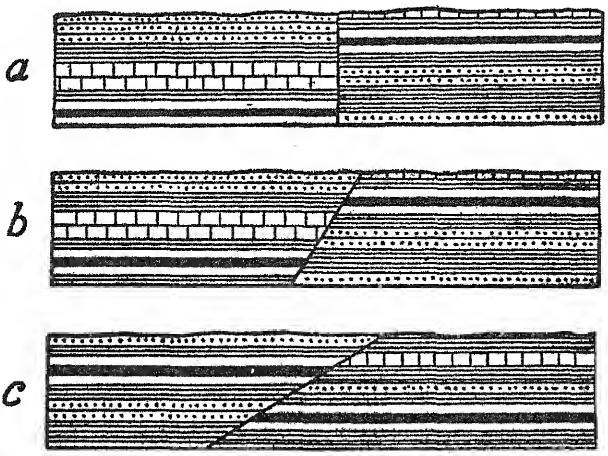


FIG. 15.—DIFFERENT TYPES OF FAULTS.
a, Normal fault, downthrow to left, fissure vertical; *b,* normal fault with inclined fissure; *c,* reversed fault, upthrow to left,

side is of the nature of a sag, with the greatest throw in the middle running out to nothing at the ends. This is certainly the case with the great Worcester fault in the Western Province of Cape Colony, which is traceable for about 150 miles and in the middle has a downthrow of at least 12,000 feet. The Pennine fault system on the east side of the Eden valley in Cumberland and Westmorland appears to be very similar on a smaller scale. It seems to fade away at the north end, while in the middle part, east of Penrith and Appleby, the throw must amount to several thousand feet. At the south end, near Brough, it links on to the Dent fault through a mass of small tilted blocks which are affected by both systems. It is not really known how the Dent fault is related to the Craven faults, but it does not seem to continue to the south of them. (See Fig. 77, p. 214.)

Since the septum of a fold is the weakest part of it, faults often tend to be formed here, and in particular overfolds often pass over into

reversed faults, as shown in Fig. 16, and if the thrusting movement continues the two ends of the same bed may eventually be separated by a considerable distance. Obviously also the hade of the fault may become very great, that is to say it may be inclined to the horizon at a very low angle; such reversed faults with an inclination approaching the horizontal and a large displacement are usually distinguished as

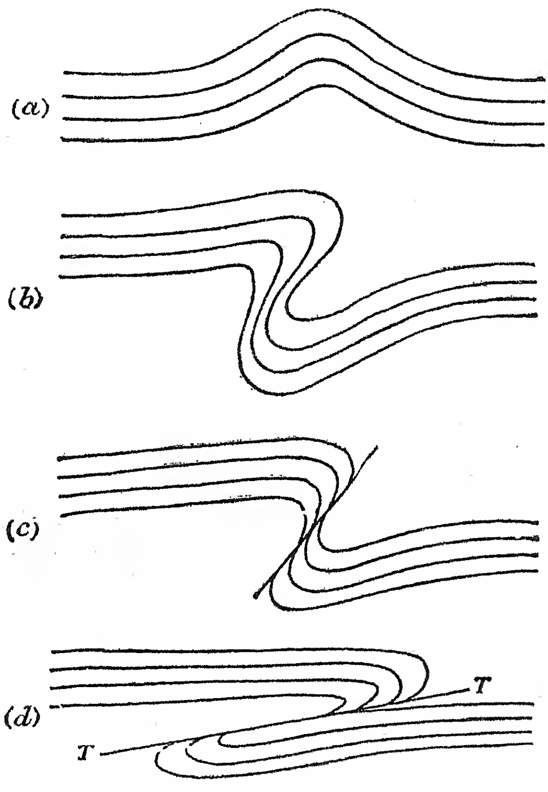


FIG. 16.—FORMATION OF AN OVERTHRUST.
a, Simple arching; *b*, becoming an overfold; *c*, septum replaced by a fault; *d*, Upper strata carried over the lower along the thrust-plane *T T*.

thrust-planes. By them one part of a set of beds is sometimes carried over another part for many miles. These *over-thrusts* often occur on a large scale in mountain chains, which have been formed by powerful folding (Fig. 17). Some notable examples are found in the north-western Highlands of Scotland, where in one case, the Moine Thrust, the displacement is at least ten miles, while in Scandinavia a similar thrust is believed to have a displacement of 60 miles.

It is very common for faults to occur in groups, in parallel, within comparatively short distances, and when this happens in the case of inclined strata it is clear that the outcrop of any particular bed may be repeated several times, as shown in Fig. 19.

Faults often produce notable effects on the topography of a region where they occur by bringing together strata of very different resistance

FIG. 17.—THRUST-PLANE AMONG THE MOUNTAINS SOUTH OF THE LAKE OF WALLENSTADT. (After Professor Rothpletz.)

1, Trias; 2, Lias 3, Cretaceous; 4, Tertiary. *T T*, Great thrust-plane; *b*, Normal fault.

to weathering, so that the harder rock may stand up like a wall, forming what is known as a fault-scarp. A good example of this is seen in Giggleswick Scar, in West Yorkshire, where a cliff of hard limestone north of the Craven fault sands up above the lower ground formed by the softer beds on the soutth side (see Fig. 18).

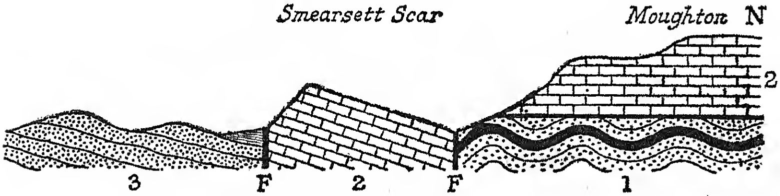


FIG. 18.—GENERALIZED SECTION ACROSS THE CRAVEN FAULTS, WEST YORKSHIRE SHOWING HOW THE CARBONIFEROUS STRATA ARE SUCCESSIVELY FAULTED DOWN TOWARDS THE SOUTH.

The total throw of the two faults is about 1,500 feet.

1, Silurian; 2, Carboniferous Limestone, Lower Carboniferous; 3, Millstone Grit, Upper Carboniferous.

Cleavage.—We have already seen how as a result of the pressure of overlying rocks there may be set up in fine-grained sediments a fissile structure known as lamination. A somewhat similar structure, but much more highly developed, frequently results from the intense pressures set up during earth-movements. Cleavage differs from lamination, however, in one important particular: lamination is necessarily parallel to the original bedding, while cleavage may make any angle with the bedding, and is very commonly more or less at right angles to it. Cleavage is a property of splitting along planes lying in a definite direction, and this direction is always perpendicular to the pressure.

As in the case of lamination, particles tend to arrange themselves

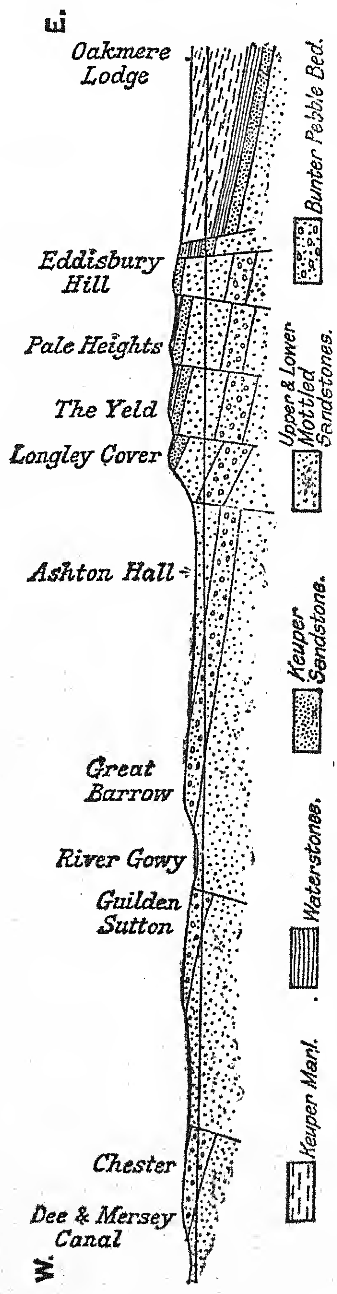


FIG. 19.—SECTION FROM CHESTER TO DELAMERE FOREST, SHOWING REPETITION OF TRIASSIC STRATA BY FAULTING.

Total length about ten miles. Vertical scale exaggerated.

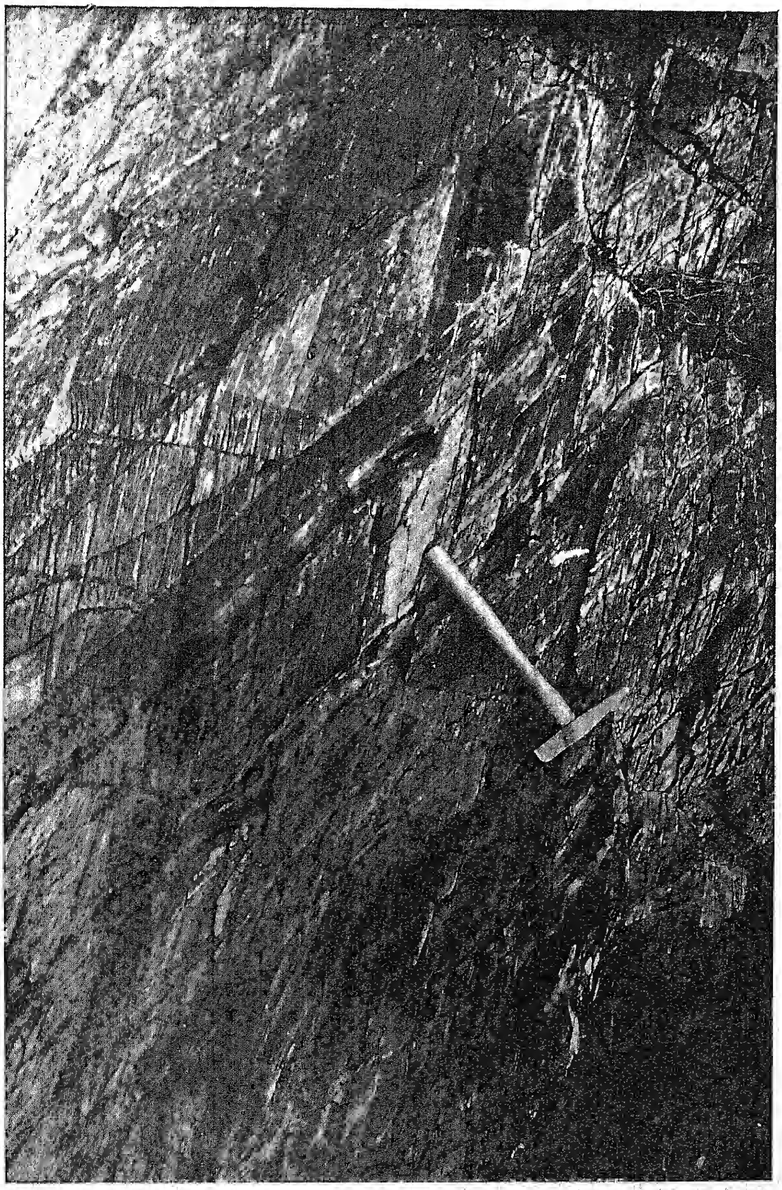


Photo by H.M. Geological Survey.

CLEAVAGE INTERSECTING BEDDING AT A HIGH ANGLE IN GREY BANDED SLATE, WADEBRIDGE, CORNWALL.

PLATE VI

Photo by H.M. Geological Survey.

(I) FOLIATED GNEISS. NEAR LAXFORD BRIDGE, SUTHERLAND.

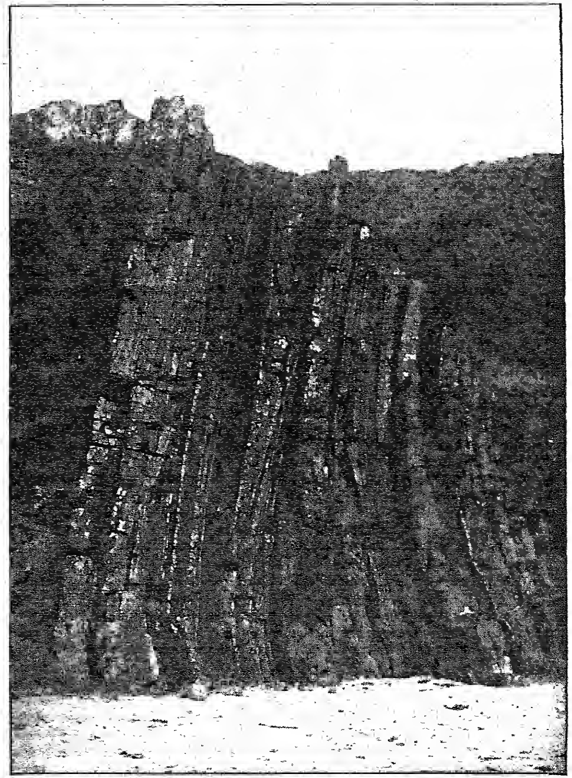


Photo by H.M. Geological Survey.

(II) VERTICAL STRATA IN UPPER OLD RED SANDSTONE. SANDTOP BAY, CALDY ISLAND, PEMBROKESHIRE.

with their long axes perpendicular to the pressure, but besides this there is always a large amount of actual deformation and shearing, accompanied by recrystallisation, so that cleavage involves a good deal of mineralogical change as well as a merely mechanical one.

For the proper development of cleavage a considerable load of overlying rock is necessary, and the process is essentially deep-seated. If the first effect of the pressure is to produce folding, fracture, and compression in rocks that are not very well consolidated, cleavage will not begin until the other effects have reached their limit, and no more relative displacement can occur; in other words, rocks cannot be cleaved until they have been packed as tightly as possible. Cleavage takes place most readily in fine-grained sediments, such as clay and shale, and also in fine volcanic ashes. The resulting well-cleaved rock is called a *slate*. Sometimes the original bedding is completely obliterated, but generally it can be distinguished by differences of colour and texture in successive bands (Plate V). This is well shown by the green stripes so common in the purple roofing-slates of Carnarvonshire, usually making a high angle with the cleavage planes. Rocks may be cleaved in more than one direction as a result of successive pressures, and will then tend to break up into various regular solid figures, instead of thin slabs.

Coarse-textured rocks, such as sandstones, do not readily undergo cleavage, and sometimes slates enclose bands of grit or limestone which have resisted cleavage, but have been folded and contorted in various ways.

Foliation.—Closely allied to cleavage is the structure known as *foliation*. This consists essentially of a parallel arrangement of the minerals of the rocks, and this parallel arrangement often induces a tendency to split in definite directions; however, this does not amount to true cleavage, as the fracture is usually imperfect and irregular. Foliation is a result of very high pressures produced by earth-movements, and it is always accompanied by a more or less complete recrystallisation of the minerals, or formation of new minerals. It affects not only fine-textured sediments, like cleavage, but also coarse-grained rocks of all kinds, both sedimentary and igneous. The rock types produced by this process are known collectively as gneisses and schists; the difference between the two classes is not very definite, but on the whole the gneisses are coarse-grained and look like crushed igneous rocks (Plate VI (i)), while the schists are finer in texture, approaching slates, and in many cases probably derived from sediments. The term 'foliation' is also used to decribe parallel structures in igneous rocks, due to flow during cooling. This is called primary foliation.

APPENDIX TO CHAPTER I

In geological maps uniformly-dipping strata often show V-shaped outcrops of varying acuteness, as will be seen in Figs. 9, 10 and 11.

The following note will explain how the direction and acuteness of such outcrops depend upon the relative dips of the strata and valley floor:—

Let XY (Fig. 20) represent the floor of the valley at any small part where the slope is uniform.

A thin bed, with an inclination also represented by XY, will outcrop along the sides of the valley as two parallel lines (*xy*, Fig. 21). Rotating such a plane, representing the bed, in a counter-clockwise direction into a horizontal position *ab*, the outcrop will follow the contour lines: that is, will become an acute V pointing *up* the valley. As the plane rotates towards

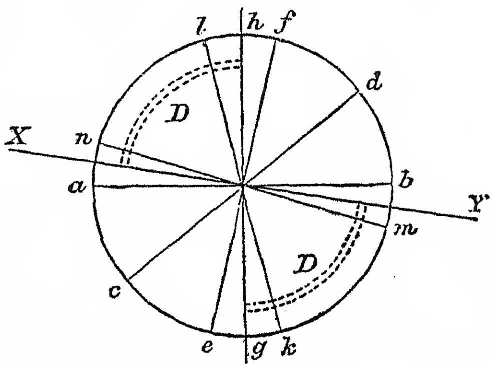


FIG. 20.—ELEVATION.
XY, Valley floor.

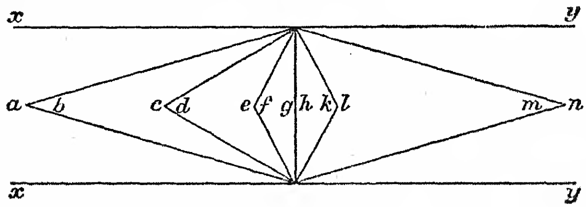


FIG. 21.—PLAN.

the vertical, the V outcrop becomes blunter, as seen in the diagrams, *ab*, *cd*, *ef*: until when the plane is vertical the outcrop lies transversely across the valley (*gh*). On further rotation of the plane the V begins to travel *down* the valley, becoming more and more acute, until the plane once more is parallel to the valley floor (*kl*, *mn*, *xy* in the diagrams).

Thus it will be seen that a bed with a dip in the area marked D in Fig. 20 (i.e. dipping down-stream at an angle greater than that of the valley floor) will have a V outcrop pointing *down*-stream; and one with a dip in the other area (i.e. dipping either up-stream, or down-stream at an angle less than that of the valley floor) will have a V outcrop pointing *up*-stream. The acuteness of the V depends on its relative nearness to the plane containing XY.

CHAPTER II

DENUDATION

Introductory.—It is a fact scarcely needing extended demonstration that the surface of the land is undergoing a constant process of destruction. Every shower of rain can be seen to carry loose material to a lower level, and in flood-time rivers are rendered turbid by the amount of solid matter in suspension. At the foot of steep slopes and precipices in mountain regions may be seen piles of angular rock-fragments obviously fallen from above, and the beds of the streams are full of subangular and rounded pebbles derived from higher levels. In desert regions an unfailing supply of sand is whirled along by the wind, and fills up the hollows: it can only be formed by the disintegration of the rocks of other parts of the desert itself. Examples might be multiplied indefinitely to show that the land-surfaces of the globe are undergoing a constant process of loss. Since the destruction of the present land affords the material from which modern deposits are being built up, to be eventually in their turn raised into land, it is logical to begin our consideration of geological processes with a discussion of the manner of origin of the raw material at the present day, and the light this casts on the processes at work in the past. We shall therefore assume the existence of the earth in its present condition, and we shall begin with a study of the processes of destruction at present in operation, comprised under the general term of *denudation*.

Climate and Denudation.—Since denudation is chiefly brought about, either directly or indirectly, by atmospheric agencies, the character and extent of the denudation in any given district are to a large degree controlled by the climatic conditions in that district. The different agents of denudation will be considered in detail in subsequent sections, but it may be said here that the most important of them are gravity, water, ice, wind and, in a less degree, plants and animals. Of these, gravity is unaffected by climate, but the rest are directly dependent on it.

From this point of view the land-surfaces of the globe may be classified under four principal types distributed in zones parallel to the equator, so that denudation is to a certain extent a question of latitude. These zones are as follows: first, there is the equatorial belt, with high temperature and heavy rainfall and consequent luxuriant vegetation. On either side of this comes a belt of high temperature and small rainfall, giving rise to more or less clearly developed desert conditions,

with conspicuous absence of plants and animals. Outside of this comes in each hemisphere the temperate zone, with a cool climate, abundant rainfall, and a thick covering of vegetation. Lastly, in the Arctic and Antarctic regions there is very low temperature, so that most of the precipitation is in the solid form, as snow: running water is rare or absent, and the conditions are those of a dry climate: there is little or no vegetation, and animal life is scarce.

These four types may be summarised as follows:—

(*a*) Equatorial belt, hot and damp.
(*b*) Desert belts, hot and dry.
(*c*) Temperate belts, cool and damp.
(*d*) Arctic belts, cold and dry.

The denudation in each of these climatic zones possesses special distinguishing characteristics, according to which of the agents above enumerated is dominant. These will be dealt with later in detail. Marine denudation is also an important subject, and requires separate treatment. It is not much affected by climate, except in the Arctic zones, where its effects are complicated by the presence of sea-ice.

Nature of Denudation.—The process of denudation is threefold: it is necessary first to consider the actual loosening and breaking up of the material; secondly, the means by which the loosened material is removed from its original situation; and, thirdly, the geological work it does during transit to its next comparatively permanent resting-place. These processes are distinguished as *Weathering*, *Transport* and *Corrasion* respectively: the sum-total of their effects is comprised under the general term *Erosion*.

(1) Weathering

Under this heading, as above stated, are to be included all the processes which bring about the actual disintegration of the rocks, and preparation of the material for the action of transporting agents (cp. Plate VII (ii)). Weathering is partly of the nature of chemical action, although many of the processes are to be regarded as mainly physical or mechanical. Rocks have already been defined as aggregates of particles, either of minerals or of amorphous matter, and it has also been pointed out that minerals are compounds having a definite crystalline form and a more or less definite chemical composition. Some volcanic rocks consist wholly or in part of an amorphous substance of variable composition, usually known as glass, but the majority are composed of crystalline minerals. Some rocks consist wholly of mineral particles, crystals or grains, while others consist in part of mineral particles and in part of some cementing material, which holds the grains together into a coherent mass. The facility with which a rock can be broken up into its component particles will evidently depend on the nature of

this cement, other things being equal. Most of the sedimentary rocks are held together by a cement which is somewhat easily broken up, so that they readily undergo mechanical weathering, and many of them are distinctly soft.

The igneous rocks, on the other hand, have crystallised from the molten state, and they are held together by the cohesion of their crystals alone: in their original form they never possess a soft cement, and may therefore be regarded as hard. This is true of the fresh, unaltered rocks: some are much more susceptible to weathering than others, so that igneous rocks do not always resist denudation better than sediments.

Chemical Weathering.—The minerals composing rocks may be regarded as chemical compounds, whose composition and physical properties depend on the conditions of their formation. If these conditions remain unchanged the minerals also will remain unaltered: that is to say they are stable. But in the course of their existence rocks are subjected to great changes, so that some or all of their minerals may become unstable under the new conditions, and will themselves undergo alteration. The general result of these processes is to break up the rock: the minerals are decomposed, and their constituents are set free to enter into new combinations, either among themselves or with substances brought in from outside. Thus a great variety of chemical reactions are set up and new compounds are formed.

Chemical Action of the Atmosphere.—The ordinary constituents of the atmosphere are nitrogen, oxygen, carbon dioxide and water-vapour, with a very small proportion of nitric acid and ammonia. Nitrogen is very inert and plays no part in weathering, and the amount of nitrogen compounds is so small that they also may be disregarded. The carbon dioxide in the air of the open country generally amounts to about 3 parts in 10,000, though it is somewhat variable. Small as this amount may seem it is of great importance, and it is clear that carbon dioxide dissolved in water plays an important part in chemical weathering. This will be discussed more fully when dealing with the effects of water on rocks and minerals.

Many of the processes of weathering depend on oxidation. Here again, however, the action is much intensified by the presence of moisture and carbon dioxide, and many processes of oxidation cannot proceed at all if the air is perfectly dry. A familiar example is the rusting of iron and steel, and the same applies to innumerable other chemical reactions.

The atmosphere contains a large and variable proportion of aqueous vapour, and this is of the utmost geological importance. There is a constant transfer of water in the form of vapour from the hydrosphere to the atmosphere, and back again, through and over the lithosphere to the hydrosphere as rain and snow, so that all the water of the land has at one time or another existed in the form of vapour in the air.

It appears, then, that it is difficult, if not impossible to separate the effects of the different gaseous constituents of the atmosphere from the effects of water in the liquid state within the rocks themselves, since these constituents, are most active when dissolved in water.

Physical Action of the Atmosphere.—Besides the chemical processes briefly enumerated above, there are certain important physical weathering agents which must be ascribed to atmospheric causes. It is well known that most ordinary solid substances expand when heated and contract on cooling. Now rocks are not homogeneous, but are aggregates of substances which behave differently in this respect. They will not act as a whole, as a homogeneous substance would do, but each individual crystal or grain will expand or contract according to its nature. As a consequence of heating and cooling great strains are set up, and fractures of all degrees of magnitude may take place. In tropical countries, and especially in dry regions where the sky is clear and radiation is uninterrupted, the difference between day and night temperatures is often very great, and the fall of temperature after sunset is rapid. In such regions disintegration of rocks by this means occurs on a very large scale, and gives rise to the great piles of angular scree material so common at the foot of mountain slopes in desert regions. In temperate climates the same process undoubtedly occurs on an appropriate scale, though its effects are usually masked by the effects due to the expansion of water in freezing.

Chemical Action of Water.—Passing on now to consider water as a weathering agent, it will be found that its effects are manifold. It has already been pointed out how the chemical activity of the gases of the atmosphere is increased by the presence of water, but besides this water has many effects peculiar to itself, and it is undoubtedly the most important agent of weathering.

Most of the ordinary constituent minerals of rocks are for all practical purposes insoluble in pure water. It is only such exceptional deposits as salt beds that are freely soluble. Calcium sulphate (gypsum or anhydrite) is somewhat soluble, as also is calcium carbonate, but the case of the last-named is complicated, as its solubility is greatly increased by the presence of carbon dioxide in the water. This subject will be dealt with later. Pure silica is hardly affected unless the water is alkaline, when it is slightly soluble, especially if in the colloidal state. But a large part of the solvent effect of natural water is due to the presence of acids, especially carbon dioxide, and sulphuric acid formed by oxidation of sulphides, such as pyrite, marcasite and pyrrhotite. A good example of the last-named process can often be seen in the corrosive effect of mine-waters and the drainings from pit-dumps, which often have a disastrous affect on vegetation, owing to their acidity. The large group of organic compounds known collectively as

the humic acids, formed by decaying vegetable matter such as peat, also help in the decomposition and solution of minerals.

As mentioned above, the case of the calcareous rocks, especially the carbonates, is specially important since the solubility of calcium carbonate is much increased by the presence of carbon dioxide dissolved in the water, when a much more soluble bi-carbonate is formed, thus:

$$CaCO_3 + CO_2 + H_2O = H_2Ca(CO_3)_2.$$

Water percolating through the rocks of limestone districts and along their fissures dissolves away the rock, often to a large extent, and may result in the formation of caverns, like those of the Mendips, Derbyshire, or West Yorkshire, or the gigantic caves of Styria and Kentucky. These caverns are the courses of underground rivers, and have in most cases been hollowed out by the solvent action of the water of the rivers working along joints previously existing in the rocks.

Oxidation is of considerable importance as a weathering agent; its effects are most conspicuous on the compounds of iron, so widely distributed and so abundant in the rocks. In most of the igneous rocks a large part of the iron exists in combination in the ferrous state, and when the complex molecules of the silicates are broken up this ferrous iron readily passes into the ferric condition. To this process of oxidation of iron is due the yellow or brown crust so common on weathered surfaces of rocks which when fresh are black, grey, green or blue in colour; and, in fact, the prevailing colour of almost all rocks depends on the state of oxidation of iron. Almost all soils show some tint of yellow, brown or red, whatever may have been the original colour of the rocks from which they were derived. Here also the change of colour is due to oxidation.

The reverse process of deoxidation or reduction is apparently not of much geological importance, and cannot be expected to occur frequently on a large scale, since under the prevailing conditions of the earth's surface the highly oxidised compounds are the more stable. The most common reducing agent in nature is organic matter, and it is to be noted that strata stained red by ferric iron often show green or white spots, doubtless due to local reduction of iron compounds to the ferrous state during decomposition of organic matter originally entombed in them.

Decomposition of Some Common Minerals.—It is impossible to give a full account of the innumerable processes of mineral decomposition that occur in nature, but it may be well to summarise as briefly as possible the changes that occur in the more important of the rock-building minerals in the list given on p. 11, when subjected to ordinary processes of weathering.

In the first place, quartz, muscovite, magnetite and garnet are exceedingly stable, being unaffected by ordinary weathering agents.

They therefore tend to survive and to be concentrated in the residues, quartz being by far the most abundant. Muscovite, however, is rather easily broken up mechanically owing to its very perfect cleavage, and is therefore often finely divided in transported deposits.

The decomposition of the felspars is very important, owing to the abundance of the minerals of this group. The subject is, however, rather complicated, as the results are not always the same, and it is not clear what the determining conditions are. The felspars are alumino-silicates of potash, soda or lime, often mixed: they are therefore salts of a strong base and a weak acid, and liable to hydrolysis. In the case of the potash and soda felspars the alkalis and some of the silica (probably colloidal) are set free and the residue is an insoluble hydrated compound of alumina and silica, which when crystallised is called kaolinite. It may be regarded as the purest form of clay-material. The lime of the plagioclase felspars in most cases eventually forms calcium carbonate. Sometimes, however, it appears that potash and soda felspars give rise to finely divided mica, which may also be regarded as a clay-mineral. Biotite is changed to a colourless mica with separation of iron, or to green chlorite, while the magnesia micas also yield chlorite. Hornblende, augite and olivine as a rule eventually decompose to some green silicate of magnesia of the serpentine group, with separation of iron as oxide or hydrate. The whole subject of the decomposition of aluminous silicates and of the constitution of their derivatives is extremely complex and cannot be dealt with here, but it may be stated briefly that such minerals in the main yield the components of clay. It is probable that all the calcium carbonate so abundant among the sedimentary rocks was ultimately derived from lime-bearing silicates in the primary rocks of the earth's crust.

Of the non-silicate minerals, pyrite reacts with water and oxygen, the final products of a complex reaction being hydrated ferric oxide and free sulphuric acid. This is a good example of oxidation in weathering. Apatite is rather insoluble, and often remains unaltered, unless attacked by fairly strong acids.

Calcite, dolomite, gypsum and rock-salt are all more or less soluble in pure water, especially the last-named. They are also easily attacked by dilute acids. In the case of rocks composed of these minerals, simple solution is the most important weathering agent.

To sum up, the chief products of the weathering of the common silicate minerals are aluminous clay-substance, secondary micas, chlorites, iron oxides and carbonates, while the carbonates, sulphates, and other soluble minerals are themselves the products of weathering and other secondary processes.

Water and Ice as Mechanical Agents.—The mechanical action of water and ice belongs rather to the provinces of transport and corrasion than to weathering, but there is one process which strictly appertains

to this part of the subject. As is well known, water differs from most other common substances in that it expands in passing to the solid state, and this expansion is large, amounting roughly to 10 per cent. The expansion also exerts enormous pressure, so that when water freezes within the cavities and interstices of a rock great strains are set up, and fragments may be broken off, or the rock shattered to a considerable depth. This agency is of great importance in cold climates and in high mountain districts, and the great accumulations of rock débris in such regions are chiefly formed in this way. Frost also plays an important part in loosening surface accumulations and rendering them more easily acted on by agents of transport. This effect can be easily seen on the surface of roads and ploughed fields after a thaw. The water in the soil expands on freezing and increases the distance between the solid particles : when the ice melts and the water returns to its original volume, or is removed altogether by evaporation, the soil is left in a spongy state, so that it is easily carried away by running water.

Action of Plants and Animals.—Besides the inorganic agents of weathering described above, a good deal of rock-destruction can be traced to the vital activity of plants and animals, especially the former. The roots of plants secrete acid juices which enable them to decompose the minerals of the soils and rocks, into which they often penetrate for long distances. They have also a considerable mechanical efficiency in widening existing fissures and facilitating the entrance of water and air. A thick covering of vegetation has also a certain conservative effect in protecting the soil from removal. As a consequence of this the surface of the ground even in temperate regions is usually covered by a thick coating of disintegrated material, formed by weathering *in situ.*

Even such lowly organised plants as mosses and lichens play their part in weathering, since they help to retain moisture on rock surfaces, and their juices also have a corrosive effect. Tufts of moss and lichens are frequently found to lie in little hollows formed in this way, and these are true rock-basins on a small scale.

The geological activity of animals lies rather in the direction of transport and deposition than of denudation. Darwin has clearly shown the importance of earthworms in bringing to the surface great quantities of finely divided soil which has passed through their bodies and is in a state fit to be easily carried away by water or wind, and the great mounds of soil piled up by ants and white ants are well known. Even moles and rabbits have a certain geological effect by scratching up material suitable for transport.

Surface Accumulations and Soils.—The ultimate result of all these processes, where not modified by transport, is the formation of a covering of loose material of varying thickness above the solid rocks of the land. However, not all surface accumulations come under this cate-

gory, since a large proportion of them have undergone more or less transport from their original situation, and some, such as river alluvium and glacial deposits, consist of material which is now at a long distance from its point of origin. These will be dealt with fully in the chapter on Terrestrial Deposits. It is a fact, however, that large regions of the earth are covered with loose material actually *in situ*. Reference has already been made to the great blankets of weathered rock in tropical regions, and something of the same sort occurs in temperate climates. It is a commonplace that when not masked by transported deposits the character of the soil is controlled by the underlying rock. The rich deep red soil of the Severn Valley on the Old Red Sandstone differs greatly from the thin whitish or grey soils of the Chalk, and these again from the sparse sandy covering of the Yorkshire moors, lying on sandstones and shales. In extreme cases the superficial layer consists only of the portion of the original rock that is unattacked by any weathering agents, like the flint gravels of East Anglia. Curiously enough the more open and higher parts of the South Downs are covered by thin red or even black flinty soil, which can only be regarded as the insoluble residue of the Chalk. Of similar origin is the Terra Rossa, which covers large areas on the limestones and dolomites of the Adriatic region and other Mediterranean countries.

An interesting example of an unusual type of residual surface deposit is to be seen in parts of the Southern Transvaal. Here large areas are covered by what appear to be masses of modern gravel, consisting of large and well rounded water-worn pebbles. These pebbles are in reality derived by simple weathering from beds of conglomerate of enormous thickness constituting a large part of the most ancient sedimentary rocks of the region, and the appearance of violent water action in recent times is wholly deceptive.

Influence of Latitude on Weathering.—Weathering is not a uniform process all over the world, its nature and extent being largely controlled by climatic conditions. From this point of view four types of climate may be recognised, as follows,—first, the damp equatorial belt; second, the desert belts; third, the temperate zones; and fourth, the Arctic regions. Hence it appears that the principal factor in determining the character of the weathering in any given area is latitude. Naturally, however, there is much variation in different parts of the world and very different conditions may prevail in the same latitude on the two sides of a continent: a good example is afforded by Natal as contrasted with South-West Africa. The central parts of large land masses often differ much from the coastal belts, and it has been said, with much truth, that in Central Asia the temperate zone is missing, the desert belt merging directly into the Arctic.

Weathering in Equatorial Regions.—In normal equatorial regions (jungle countries) owing to high temperature and excessive rainfall

chemical weathering is specially active and thick vegetation hinders transport. Hence in many places the rocks are thoroughly decomposed down to very great depths, sometimes 100 feet or more. Among the igneous rocks formation of kaolinite and laterite is specially characteristic as hereafter described, while sedimentary rocks are rapidly disintegrated: by removal of the cement in the case of sandstones, conglomerates and even quartzites, while shales, slates and schists are converted to soft clay. Naturally also limestones are rapidly dissolved, even deep underground, and extraordinary effects are sometimes produced by collapse of overlying less soluble strata into cavities left by underground solution of limestones. A notable feature of tropical weathering, difficult to explain, is the extreme sharpness of its lower limit, in many cases. Sometimes in a quarry it is seen that the passage from completely rotten to hard, fresh rock takes place almost in the thickness of a knife-blade. It is a moot point whether bacterial action plays a part in this kind of rock-decay. The high temperature of the ground-water, often up to 80°, would naturally be favourable, and the possibility must be taken into account, though there is no proof.

Weathering in Desert Regions.—In those parts of the world specially characterised by a dry climate and consequent absence of vegetation, that is to say in deserts, peculiar conditions prevail, and the character of the weathering differs a good deal from what is found elsewhere. True deserts chiefly occur in more or less continuous zones on either side of the equatorial belt, and in the majority of cases the temperature is high, at least during the day, while the nights are often cool or even cold. Consequently the daily range of temperature is very great, so that here the effects of alternate expansion and contraction have full play, and it appears that true desert sands may be formed by the simple breaking up of rocks into their constituent crystals by this means, without perceptible alteration of the minerals themselves.

Although ordinary rainfall is practically absent, now and then, even in the driest regions, there are violent rainstorms and cloud-bursts, so that there is always a certain amount of ground-water in depth. Since the air is always very hot and dry, this water travels upwards by capillarity, carrying with it salts dissolved out of the rocks. These salt solutions react with the minerals of the rocks near the surface and decompose the less stable ones, causing disintegration. This effect, combined with rapid changes of temperature, often causes the surface of the rock to separate in scaly or platy masses, which on steep faces fall off and accumulate as great screes at the foot (the *desquamation* of von Richthofen). The surface layers of sand on the flatter ground are often cemented by crystallisation of the salts thus brought up, and sometimes stained yellow or red by iron. However, the red colouration of desert sands, so strongly insisted on in most textbooks of geology,

has been greatly exaggerated: deserts are usually pale yellow or grey, like the sands of the seashore.

A very common phenomenon in desert regions is a brown or black shiny crust on the rocks, the so-called 'vernis du désert,' which consists of oxides of iron and manganese. It is probably due to evaporation of water brought up by capillarity, containing salts of iron and manganese and chlorides in solution. It is thoroughly characteristic of deserts, both ancient and modern, and according to Walther it affords a sure test of the prevalence of such conditions.

Weathering in Temperate Regions.—The type of weathering prevailing in regions of temperate climate is to a certain extent a combination of all the others, but naturally each exists in a less marked degree than in districts where the climatic conditions are more extreme. There are also to be noted considerable seasonal variations. In winter frost action is dominant, whereas in summer water plays a more conspicuous part. It is only in specially dry seasons and in localities where the climate is unusually arid that wind action and dry weathering are of any importance. It must, however, be borne in mind that climatic conditions, and especially the rainfall, show wide variations within very limited areas. To take one case only, the average rainfall of the western coast of the British Isles is much higher than that of the east coast, so that it is difficult to compare the activity of weathering processes in the two regions. Elevation above sea-level is also an important factor, and even in the comparatively low mountains of the British Isles the higher portions show conspicuously the effects of frost-shattering. Temperate regions are much less subject than others to sudden changes of temperature, so that this agent produces only a small effect. On the whole, perhaps, solution and chemical disintegration are the dominant features of weathering in these regions, while frost action is restricted to a small part of the year, but is very efficient while it lasts.

Weathering under Arctic Conditions.—Owing to the low temperature, chemical action is less vigorous and the organic agencies are almost inoperative. By far the most important weathering agent is the expansion of water on freezing, which shatters the rocks, breaking them up into markedly angular fragments. This is the cause of the strikingly sharp peaks and ridges so characteristic of the mountains of high latitudes, and of the highest peaks in other regions above the snow-line. Under these conditions decomposition of minerals is at a minimum, and the dominant process is disintegration, which leads to the accumulation of great masses of fresh rock-material. Over the permanently snow-covered areas of the arctic zones weathering must be almost non-existent.

(2) Transport and Corrasion

The material loosened by the various processes of weathering described in the last section is subjected to further influences which remove it from its former situation and deposit it elsewhere, and these processes of removal are summed up under the general designation of *transport*. To effect transport mechanical energy is required, and this energy is supplied by gravity acting alone, by wind, and by moving water and ice.

Every moving particle is capable of doing a certain amount of work; and the kinetic energy of the transported particles, whether falling freely under the influence of gravity or carried along by wind, water or ice, is able to overcome the cohesion of other particles, so that rock-fragments, when once loosened from their beds, form effective graving tools by which the surface is carved out. It is difficult, therefore, to separate clearly the effects of transport and corrasion, as the latter process goes on concurrently with the former. It will be most convenient to consider the two processes together, since to treat them separately would involve much needless repetition.

Agents of Transport.—The chief agents of transport are: gravity, wind, and especially water both in the liquid form and when solidified into snow and ice. Besides these, other agencies sometimes come into play to a small extent, such as animals and birds, which may carry small quantities of material for long distances, and by their burrowing and scratching sometimes facilitate the effects of wind, gravity or water. The results are so small as to be practically negligible.

Gravity.—When material is disintegrated in any of the ways described above under the head of weathering, the action of gravity tends to cause it to seek a lower level. When rock-fragments are broken from the face of a cliff or from a steep slope, either by expansion of freezing water or by changes of temperature, they will fall or roll to the bottom, and will there give rise to those accumulations of fallen material which are so conspicuous a feature of mountain scenery in all climates. These accumulations are known as *screes*, and some very fine examples are to be seen in the English Lake District: the well-known screes on the south-east side of Wastwater may be specially mentioned.

A similar effect on a smaller scale is universally found wherever rocks are being weathered *in situ*: if the slopes are steeper than the natural angle of rest of the loose material, this will slide down and will accumulate at the foot. It appears that for this reason there is a constant slow downward creep of soil and loose material on all slopes, but this effect is in part due to the presence of water.

Material falling under the influence of gravity possesses kinetic energy, and is capable of doing work. It can often be observed that when a block larger than usual has fallen down a scree-slope its path is

marked by a trail of fresh fractures and well-marked scratches on the weathered surfaces of the older fragments. This shows that every falling block does its share in comminuting the older fragments, that is to say, it helps in the process of corrasion.

Landslips.—In mountainous and hilly regions, where slopes are steep, and on sea-coasts bounded by cliffs, landslips are undoubtedly a geological agent of first-class importance. They are extremely common in nearly all parts of the world, but for their full development on a large scale rather special conditions are required. A steep slope alone does not necessarily produce a tendency to slips, but both the inclination of the rocks themselves and their character have to be taken into account. A dip in the same direction as the slope of the surface naturally favours slipping, but in most large landslips it seems that water is undoubtedly an important agent, acting partly by softening and wearing away porous or incoherent strata, and partly as a lubricant. Some of the most extensive landslips in the British Isles are to be seen in Kent, in the Isle of Wight, and on the Dorset coast near Lyme

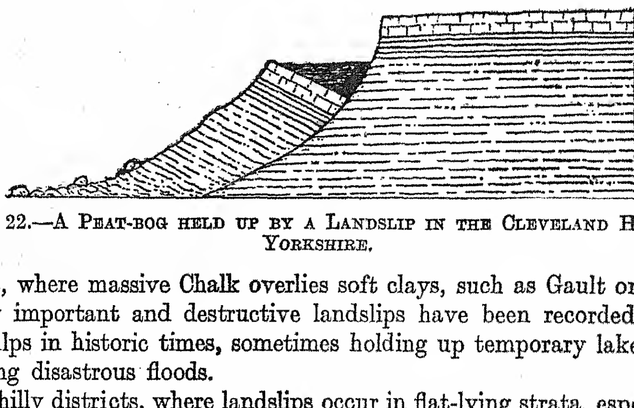


FIG. 22.—A PEAT-BOG HELD UP BY A LANDSLIP IN THE CLEVELAND HILLS, YORKSHIRE.

Regis, where massive Chalk overlies soft clays, such as Gault or Lias. Many important and destructive landslips have been recorded from the Alps in historic times, sometimes holding up temporary lakes and causing disastrous floods.

In hilly districts, where landslips occur in flat-lying strata, especially where the hills have a cap of hard rock overlying softer beds, it can often be seen that the slipped portion has a markedly curved lower surface and becomes tilted during its descent. Peat bogs or even small lakes, such as Gormire near Thirsk, often form in the hollows thus produced (Fig. 22).

It is obvious that in areas where such slipping is frequent great care is necessary in geological mapping, to make sure that any given outcrop is really in place.

During violent rain-storms and cloud-bursts land-slipping is often very conspicuous and in rivers running in narrow gorges it often intensifies the destructive effect of floods by temporarily damming the water, thus creating an extra rush of water when the dam bursts. This is often the cause of the destruction of bridges. Among well-wooded

mountains in tropical regions of violent and heavy rainfall, landslipping of this kind seems to be the most important agent of erosion; the scars thus formed are often very conspicuous on steep, jungle-covered hills.

Closely allied to land-slipping is the cracking and slow sliding of slices of boulder-clay on steep hillsides, and in fact it is impossible to draw any sharp distinction between sudden and conspicuous landslips and the slow creep that is so common in many clay formations. Evidence of the process is abundant in the British Isles, and even in an area of such low relief as the district round Kettering and Northampton it is clear that there has been much slipping of the harder limestones and ironstones over the Lias clays in the valleys.

Although the direct action of gravity is comparatively of minor importance in geology, it must not be forgotten that the power of water, snow, and ice as agents of denudation is ultimately due to gravity.

Wind as a Geological Agent.—In our own country and in other temperate climates the geological effects of wind are not very conspicuous, partly because of the thick coating of vegetation which acts as a shield for the loose material, and partly because of the prevailing dampness, which prevents the formation of dust to any great extent. It is only in certain sandy districts, such as the country round Aldershot and in parts of East Anglia, and on the western coasts of the island, that wind action is of any considerable importance. To obtain a true conception of the geological importance of wind we must turn to a desert region, where it is by far the most potent agent of transport and corrasion. (See Chapter IV).

Transport by wind possesses one special peculiarity in that material may be, and often is, carried uphill against the influence of gravity. This peculiarity is to a certain extent shared by ice transport. Fine dust may also be carried by wind over water areas, and this is by no means uncommon. The rain which falls in the south of Europe, for example in Sicily, is often quite turbid owing to solid matter in suspension, derived from the deserts of Africa, and this affords a means by which small organisms and spores and germs of larger organisms may be distributed over wide areas. In volcanic eruptions also enormous quantities of fine dust are carried into the air, and spread far and wide. The dust from the eruption of Krakatoa in 1883 was carried by air-currents in the upper layers of the atmosphere all over the world, and produced remarkable sunset effects even in Europe.

CHAPTER III

RIVERS

Running Water as an Agent of Transport and Corrasion.—Under temperate conditions of climate and general surroundings, by far the most important agent of transport and corrasion is running water. It may be said that in temperate latitudes with a normal rainfall the existing relief of the land is due almost entirely to this cause, the effects of gravity and wind being very subsidiary.

From the point of view of the study of river development it is unfortunate that so much of North-western Europe, including most of the British Isles, and also a large part of the United States, were subjected in geologically recent times to intense glaciation, which introduced innumerable complications into their topography and rendered its elucidation extremely difficult. Furthermore, until surprisingly recent times British geologists were obsessed by the idea that plains and broad valleys had been excavated by the sea, and that narrow valleys and gorges were cracks in the earth caused by earthquakes: all this was a relic of the catastrophic theories of the eighteenth century. It was only when the subject was taken up seriously in the unglaciated regions of the western United States and especially in the Great Basin, where the geology is on the whole very simple and on a large scale, that true enlightenment began. The earliest attempt in this direction was Gilbert's classical 'Report on the Geology of the Henry Mountains,'[1] while later his conclusions were much extended by I. C. Russell and W. M. Davis,[2] and the last-named afterwards extended his work to some of the rivers of the British Isles, notably the Thames and the Severn.[3]

The Energy of a Stream.—The starting-point of Gilbert's theoretical conclusions is the conception that every stream possesses a definite amount of energy, depending on its volume and velocity. The volume of a given stream is regarded as a fixed quantity; but the velocity depends on several other factors, and in particular on the gradient. Friction between the flowing water and the sides and floor of the channel is also taken into consideration, so that the form of the channel is also of great importance. The energy of a stream is partly utilised

[1] Gilbert, *Report on the Geology of the Henry Mountains*. Washington, 1880.
[2] Davis, *Physical Geography*. Boston, 1898. Russell, *River Development*: Progressive Science Series. London, 1903.
[3] Davis, 'The Development of certain English Rivers.' *Geogr. Journ.*, v. 1895, p. 127.

by friction and partly by the transport of solid matter in suspension. As the energy is a fixed amount, there is evidently a close relation between friction and transport, since their sum is a constant.

Material which is simply carried along in suspension has little geological effect, but the coarser particles rolled along the bed of the stream perform work by means of the energy imparted to them by their movement. Every moving fragment striking the sides or bottom of a stream has a certain effect in overcoming the coherence of the rock over which the stream flows, and thus removing particles which can be carried away by the running water. This is the most important part of corrasion. The tools employed are rock-particles carried along the bottom of the stream, and the driving force is the energy of the stream itself. We thus see how closely connected are the two processes of transport and corrasion.

Load of a Stream.—It is evident that a stream of a given volume and velocity will be able to transport a certain definite amount of solid material, and this is called the *load* of the stream. Theoretically, the total weight which can be carried should be unaffected by the state of division of the material, provided the size of the particles did not exceed the maximum which could be transported by the given stream; but it is found that in reality a stream can carry a larger load of fine detritus than of coarse, or, as Gilbert puts it, it is easier to carry ten particles of one grain than one particle of ten grains. Hence the effective load of a fully loaded stream depends on the fineness of division of the particles. In a fully loaded stream any further addition of material must be balanced by dropping an equivalent quantity of the load already carried; corrasion and deposition must be equal, and the stream cannot cut down vertically. A stream with no load does very little corrasion. Therefore, there must be some intermediate load for which the effective vertical corrasion is at a maximum. Where, on the other hand, the load brought into any part of a stream is too great, deposition must occur.

It was pointed out many years ago that increase of velocity increases the transporting power of a stream in much more than the simple ratio, and Hopkins showed that the weight lifted should vary theoretically as the sixth power of the velocity. However, it is found by experiment that the actual ratio is somewhat less than this. The very rapid increase of transporting power as the velocity rises explains the powerful effect of floods. If a stream during a flood runs three or four times as fast as usual, its transporting power will be multiplied several hundred times, and it will be able to carry with ease boulders which at other times would be quite immovable.

The Curve of Erosion.—In the case of most streams the upper part of the course is the steepest, while near the mouth the slope, and consequently the velocity, becomes less. This decrease of velocity

diminishes the power of transport, and some of the load must be thrown down. Hence it follows that a stream deposits material in the lower part of its course while it is still corrading near its head. In the same way minor variations of slope in the course of a stream will lead to alternate regions of deposition and corrasion. Suppose that at some period of its existence the course of a stream, seen in vertical section, shows the form illustrated in Fig. 23 (continuous line), with an alternation of steep and gentle slopes. Where the slopes are steepest corrasion

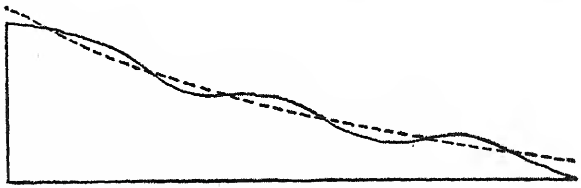


FIG. 23.—GRADING OF A RIVER-BED.

will take place, and where they are gentle deposition will occur, so that eventually the whole is planed down and levelled up to one uniform slope (dotted line). Such a river-bed is said to be *graded*. If the volume of water and rate of erosion remained uniform throughout, this graded slope would be represented in section by a straight line, but under natural conditions this is not the case. The volume of water increases from the head downwards, while the rate of erosion is less near the sea, since the stream cannot cut down below sea-level, and the limit is soon reached in this part of the course. Erosion is also less near the head in consequence of the smaller volume of water. The ultimate result, therefore, of stream erosion is to produce a curve with the concave side upwards, which is commonly known as the curve

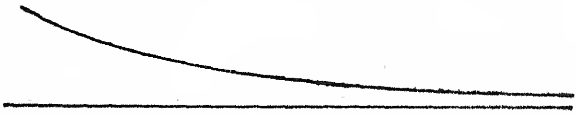


FIG. 24.—CURVE OF WATER EROSION.
(*It is a logarithmic curve.*)

of water erosion (Fig. 24). This is the form towards which the beds of all existing streams are tending: many of the sluggish rivers of the eastern and midland counties of England have attained it in an excessively flattened form, having a regular slope from source to mouth, unbroken by any sudden changes of slope. On the other hand, most of the rivers of the north and west show numerous rapids, waterfalls and other inequalities in their courses, which prove that they have not yet reached their lowest level of erosion, but are still engaged in planing off projections and filling up hollows, in the endeavour to attain to

the uniform curve above described. When a river has reached a stage at which it can no longer appreciably deepen its course it is said to have reached its *base-level*; this term is of American origin, and is rather a misnomer, since the line attained is not horizontal or a level in the ordinary sense of the word, but a curve lying in a vertical plane. *Base-line of erosion* would be a much better term.

It is much to be wished that some suitable word existed in English to express the course of a stream considered in a vertical plane. For this purpose the German term *Thalweg* is generally employed. It might well be called the valley-track, which is the literal translation of Thalweg.

In streams which have reached base-line the thalweg is a uniform logarithmic curve with the concavity upwards, while in younger streams, and those still actively corrading, the thalweg is an irregularly curved line.

The Law of Structures.—Rate of erosion is influenced by the character of the rocks, and especially by their hardness. Since the soft rocks are worn away more rapidly, the hard ones are left as elevations, and this differentiation will continue to become more marked until the soft rocks have reached their base-line of erosion. But the hard rocks are then still undergoing erosion, and this will continue till these also are worn down to base-line. When this is accomplished the differences in elevation will have disappeared, so that the law of structures is only strictly true in the youth and middle age of a region of denudation, and not for the later stages, or maturity. However, with this limitation it may be said that the topographical forms of the earth's surface are primarily due to differences in the hardness of the rocks of which it is composed.

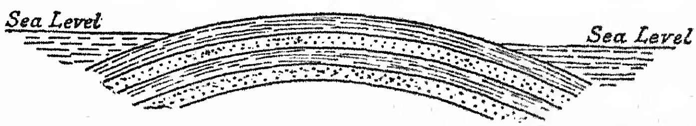


FIG. 25.—CONTINENTAL UPLIFT IN THE FORM OF AN ANTICLINE.

Development of a Typical River-system.—The starting-point of modern theories of the development of drainage-systems is a plain of marine sedimentation, which is uplifted in the form of a simple arch or anticline on a continental scale (Fig. 25). In this simple case the dip of the beds composing the arch will be away from the axis of elevation on either side towards the sea, while the strike is parallel to the axis. Rain falls on the new land surface and tends to run down the slopes along the dip. The rain which falls on the top of the arch sinks into the ground to a certain extent, and issues again as springs a little lower down the slope.

Consequent Streams.—It is assumed that the springs would rise from the ground at approximately equal distances apart, at the corners of a series of equilateral triangles, so that the arrangement of the springs

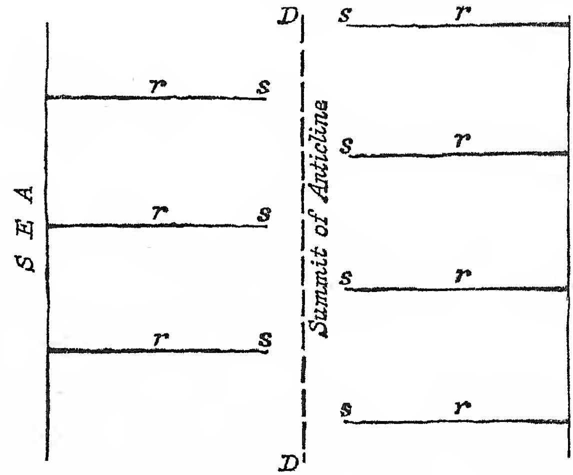


FIG. 26.—INITIAL STAGE IN THE DEVELOPMENT OF A RIVER-SYSTEM.
s, *s*, Springs; *r*, *r*, Rivers; *D*, *D*, Axis of uplift, forming the main divide or watershed.

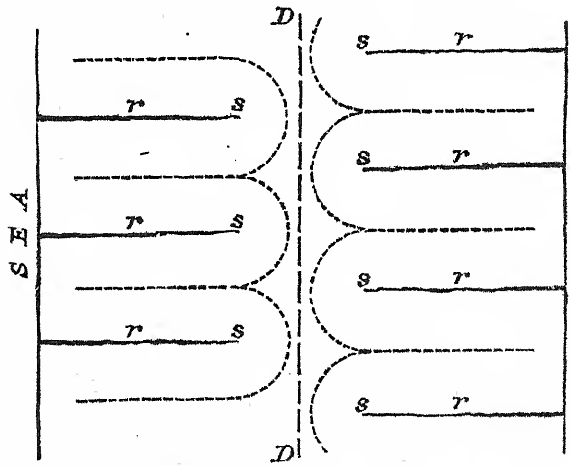


FIG. 27.—FURTHER DEVELOPMENT OF THE SYSTEM.
s, *s*, Springs; *r*, *r*, Rivers; *D*, *D*, Main divide. The dotted lines define the area drained by each river.

on each side of the watershed or divide would be as shown in Fig. 26. The result of this arrangement is the development of two series of streams, arranged alternately on either side of the divide, and flowing

straight down the slopes of the uplifted continent to the sea. These are called *consequent* streams, because their formation is a direct consequence of the uplift.

In a short time the effects of denudation make themselves manifest, and their first result is the formation of a half-funnel-shaped hollow round the head of each stream, leading down to a straight valley below (Fig. 27). After a time these hollows encroach on each other, so that from the head of each two passes or cols lead over into the upper parts of the adjoining valleys on either side, while the ground between them stands up as a mountain peak.

Thus we have a watershed or divide of zigzag form separating two series of alternate valleys, each of which has a mountain peak at its head, and from the opposite side of this peak there runs a long ridge,

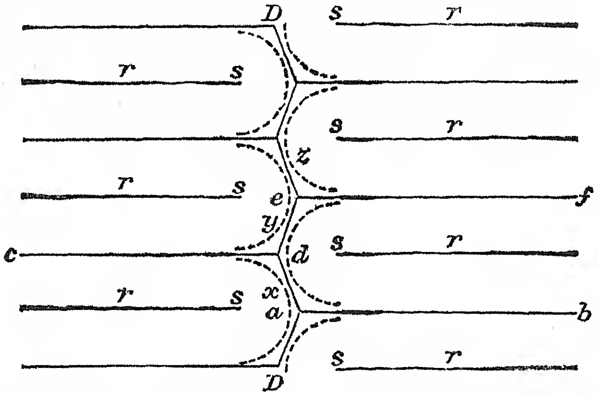


FIG. 28.—*D*, *D*, Main watershed, with zigzag outline; *ab*, *cd*, *ef*, Secondary watersheds; *a*, *d*, *e*, Culminating peaks; *x*, *y*, *z*, Cols, or passes; *r*, *r*, Rivers

forming the secondary divide between two adjacent valleys (see Figs. 28 and 29).

This simplicity of structure is not often maintained, but there is an approximation to it in the case of the chain of Monte Rosa [1] and elsewhere. In spite of many local modifications the zigzag form of the main divide of a district is often recognisable.

The form assumed by the thalweg of a stream under normal conditions, the curve of water erosion, has already been discussed, and it is evident that a section through the ideal continent at right angles to the axis of uplift will show a double curve of the type shown in Fig. 30. The dotted line in the figure indicates the original outline of the continent, which is supposed to have been produced by a symmetrical uplift. We should therefore expect such a region to possess a comparatively level surface near the sea, with slopes gradually increasing in steepness upwards, and culminating in a central mountain-range.

[1] Marr, *Scientific Study of Scenery*, 1900, p. 77, Fig. 15.

This is precisely the structure which is found in the majority of land masses, and it is clearly displayed in the north of England. There are in Northumberland, Durham and Yorkshire a number of large rivers running more or less parallel to one another in an easterly direction to the North Sea: all of these take their rise from a central watershed, the crest of the Pennine chain. These afford the best example in Britain of primary consequent streams of this type. On the western side the symmetry is spoilt by the later dome-shaped uplift

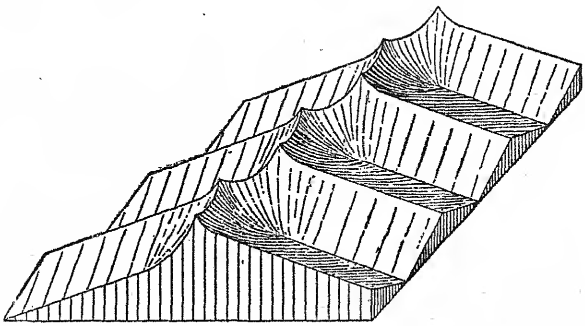


FIG. 29.—BLOCK DIAGRAM OF WATERSHED PHENOMENA SHOWN IN PLAN IN FIG. 28.

of the Lake District and the greater steepness of the Pennine chain itself on this side. Hence the rivers of the western slope are much less regularly arranged than those of the eastern side.

Subsequent Streams.—So far it has been assumed that the streams are simple and constant in volume, without regard to the additions received in the lower parts of their courses, but in reality this is not so. Rain is constantly falling on the land, and must be carried off by

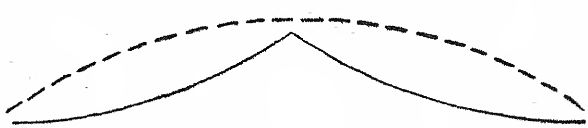


FIG. 30.—SECTION ACROSS CONTINENTAL ARCH.
Showing curve of water erosion on either side of the axis. Dotted line = original surface of arch. Full line = double curve.

surface drainage. Since the conditions are never uniform the effect of denudation will be to produce an uneven surface; the rainwater will collect in the hollows and will form subsidiary streams, with secondary watersheds between them. The subsidiary streams flow into the main streams as *tributaries*, and the position and distribution of these secondary streams are determined by the geological structure of the land, since they depend primarily on differences of hardness of the underlying rocks.

Let us consider briefly the simplest case, that of a series of originally horizontal strata, uplifted into a continental arch and denuded as before described; and let us suppose that these strata are composed of alternate hard and soft beds. Here the effect of denudation will be to expose alternate bands of hard and soft rock, forming a series of ridges and hollows parallel to the axis of the country and at right angles to the consequent streams. The tributaries will flow along the hollows thus formed, and they are known as *subsequent* streams, because they are formed after the consequent streams (Fig. 31).

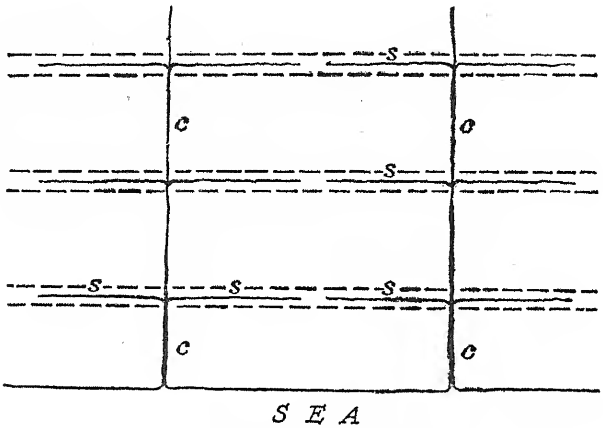


FIG. 31.—PRIMITIVE RIVER-SYSTEM,
Consisting of consequents, or dip-streams, *c, c*; with tributaries, subsequent or strike-streams, *s, s,* flowing in soft strata.

If we regard further the relations of these two sets of streams to the underlying beds we shall see that the first set flows down the steepest slope, or dip-slope, of the underlying beds, while the second set flows at right angles to this, or parallel to the strike of the beds. Hence consequent and subsequent streams may be spoken of as dip-streams and strike-streams respectively.

River-capture.—Fig. 31 shows the type of river-system which might be developed in a region where perfectly uniform conditions prevailed, but actually such uniformity does not exist. As a result of the diversity of structure and conditions which always occurs in nature, many complications are introduced. In particular the rate of erosion varies in different streams, owing to variations in declivity, volume of water, and other factors, so that some will work backwards more quickly at the head, while others will carve out a deeper valley. In these and other ways the symmetry of the system is destroyed, and in some cases the waters of one river may be diverted into another.

Let us suppose that in Fig. 32 the subsequent stream *b*, a tributary of B, is so much more active than the corresponding stream *a* that it has driven back the watershed between the two to *d*, and has been thus enabled to capture the drainage-water which originally flowed into the head of *a*. The extra volume of water thus acquired will still further increase the activity of *b*, so that in course of time it may be able to

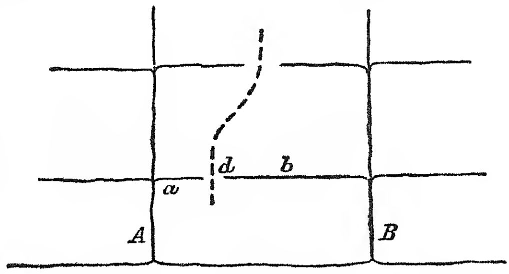


FIG. 32.—INITIAL STAGE IN RIVER-CAPTURE.
The secondary divide, *d*, receding before tributary *b* towards *a*.

cut completely through the secondary divide *d*. If the level of *b* is here lower than that of A at the point of junction of A and *a*, the water of stream A must be switched off down the valley of *b*, and the lower part of A will be deprived of its water (Fig. 33). This process is known

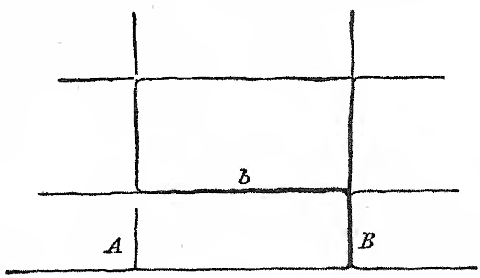


FIG. 33.—RIVER-CAPTURE OR BEHEADING.
The upper waters of A have been diverted by tributary *b* of river B.

as river-capture, and stream A is said to be beheaded by *b*, a tributary of B.

In this case the lower part of valley A is left dry, or with an insignificant stream only, which appears to be too small to have eroded the valley in which it flows. Such a stream is called a *misfit*.

At the head of the lower abandoned part of valley A is a broad pass or col, leading into valley *b* opposite the great bend of the river. Such

a notch at the head of a valley is called a *wind-gap*, and it often gives a clue to the history of the valley.

It is evident that by a long continuance of processes of this kind very complicated drainage systems may be produced, since one particularly active stream may successively capture a large number of others. Such appears to have been the history of the development of the present main drainage system of Yorkshire and Durham (see Fig. 34). Leaving out of account certain complications in the eastern part due

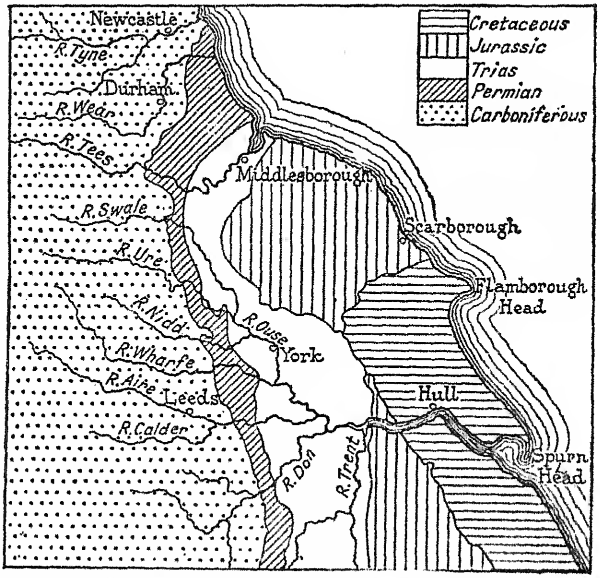


FIG. 34.—MAP OF THE OUSE RIVER-SYSTEM.

to glaciation, the origin of the rivers of this region appears to have been somewhat as follows:

It may be assumed that the system was initiated as a series of dip-streams, consequent upon the uplift of the Pennine chain. This uplift gave rise to a series of rivers flowing eastwards down the dip of the strata to mouths far beyond the present coast-line of England. These rivers were the forerunners of the present ones, Tyne, Wear, Tees, Swale, Yore, Nidd, Wharfe, Aire, Calder and Don. The more northerly of these, Tyne, Wear and Tees, have undergone comparatively little change, and are still on the whole consequent streams. With the rest of the rivers enumerated the case is very different. They no longer form independent consequents, flowing separately to the sea, but all unite to form one great river, the Ouse, which joins the Trent, and the two together form the wide estuary of the Humber. The course of the Ouse is approximately north and south, and it flows in the broad belt

of soft strata formed by the outcrop of the Trias. This fact is significant, and probably affords the explanation of the whole phenomenon. The present course of the Aire may be regarded as a direct continuation of the Humber, and this forms one consequent stream. This consequent developed subsequents, and one of these, working back along the soft Triassic strata, was able to capture the next consequent, and so on successively for the rest. The Ouse, however, has not yet succeeded in capturing the head waters of the Tees, although the watershed between them has been reduced, by the working back of the tributaries of the Ouse, to only 150 feet in height.

Dip-slope and Escarpment.—The Law of Structures states that hard masses tend to stand up as eminences, while soft ones form

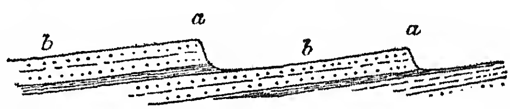


FIG. 35.—SECTION ACROSS ESCARPMENTS, ALONG THE DIP.
a, *a*, Escarpments; *b*, *b*, Dip-slopes.

hollows, and this law makes itself manifest in the relief of an area undergoing denudation by river erosion. Assuming simple ideal conditions, as before, the tract in question will be traversed by a

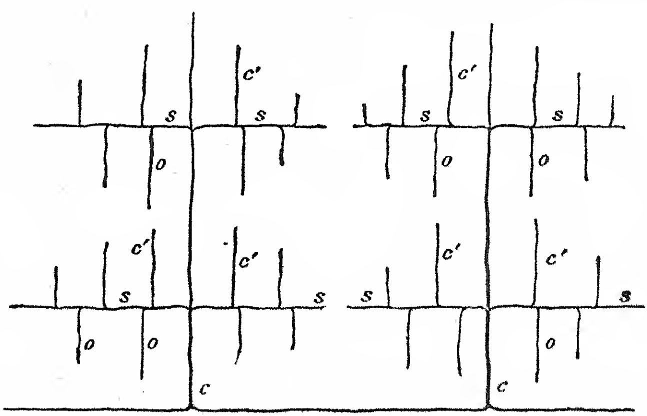


FIG. 36.
C, *C*, Consequent streams; *s*, *s*, Subsequent streams; *o*, *o*, Obsequent streams; *c′*, *c′*, Secondary consequent streams.

series of subsequent valleys, parallel to the coast and at right angles to the consequent streams. Since the general dip of the area is towards the sea, each of these valleys will be limited on the seaward side by a

steep slope or *escarpment*, and on the landward side by a gentle dip-slope. This can be well seen in the case of some of the larger valleys of the eastern Midlands. The valley of the Cam and Great Ouse is bounded on the south-east by the escarpment of the Chalk, which is comparatively steep, and on the north-west by the very gentle slopes of the Lower Cretaceous and Upper Jurassic beds, which here dip to the south-east at a very low angle. Owing to the contour of the ground these escarpments do not form straight lines, but assume a curved form. When denudation has proceeded so far that these scarp-slopes attain a considerable size, they may themselves give rise to small streams, tributaries of the subsequents: these will flow in a direction opposite to that of the consequents, that is, away from the sea. They may also be described as flowing against the dip of the beds. Streams of this kind are distinguished by Davis as *obsequent* streams (*o*, *o*, *o*, in Fig. 36). In a similar way small secondary consequents will develop on the dip-slopes (c', c', c'), so that the whole system eventually becomes very complicated. Of course, in nature the extreme regularity and rectangular arrangement shown in these diagrams is never attained. One important modification is introduced by a general tendency of the junction point of two streams to move downhill and a well-developed river system often shows in plan a strong resemblance to the branches of a tree, tending to be fan-like rather than rectangular. This is well seen in the map of the Yorkshire rivers (Fig. 34).

Meanders.—When a stream has reached its base-line of erosion it can no longer cut downwards; but it still possesses energy, which must be used up somehow, and this energy is employed in lateral corrasion. So long as a stream is quite straight the corrasive effect on both banks is equal, but so soon as any deviation from straightness occurs the current impinges with greater force on the concave side of the curve, so that the banks on that side are eroded, while there is a tendency for deposition to occur in the slack water on the convex side, so that the course of the stream is gradually shifted and the curves become more and more marked. In sluggish streams flowing through level tracts this formation of curves goes on to a great extent, and gives rise to what are known as *meanders* (Fig. 37). Many of our English rivers exhibit the phenomena of meandering in a very high degree. This process obviously occurs at a late stage in the life-history of a river, and very pronounced meandering may be taken as an indication of old age.

In many cases the amplitude of these curves becomes great and the windings complex, so that the distance separating two points of the course may be very small in a straight line, although a long length of river channel may intervene between them. In some cases the river may eventually break through the narrow neck of land separating the two reaches, abandoning the intermediate part of its channel. Such

diversions are specially prone to occur during floods, and are much assisted by the steeper grade which must exist between two such points, as compared with the old channel. Such abandoned channels are common along the lower reaches of many large rivers, and along the lower course of the Mississippi they have given rise to a series of crescent-shaped lakes, which are there known as *ox-bows*. Similar structures on a small scale may be seen along many a winding English stream.

Meanders not only tend to increase in amplitude and complexity, but the whole curve moves bodily down-stream, since the current always sets more strongly against the down-stream bank. Thus in course of time a river may work over a very considerable area of ground, and will give rise to a large level plain, or alluvial flat, which is bounded on either side by fairly steep slopes. A plain formed in this way is called a meander-belt, and within this area the whole of the soil must consist of material which has been sorted and redeposited by river action, down to the base-line of erosion. Such flood plains are very commonly bounded on either side by a steep slope, which in the normal case in cross-section appears as a notch cut in the solid rock of the valley side. Since at one time or another the bed of the river has occupied every point in the meander plain, it is filled to the average depth of the stream with alluvium deposited by the river: gravel, sand or silt, according to the velocity of the stream at the time of deposition of each. Below this alluvium comes the eroded surface of solid rock.

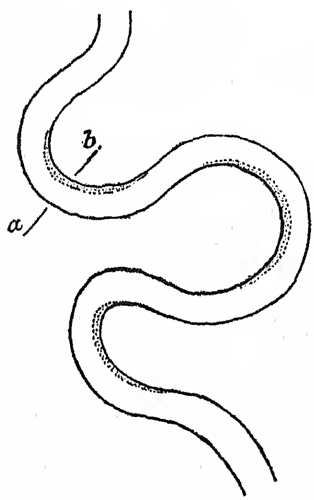


FIG. 37.—RIVER MEANDERS, SHOWING DEPOSITION AT THE CONVEXITIES.

In hilly districts, however, with steeply graded streams, meandering is much less conspicuous. Nevertheless, most valleys soon depart from ideal straightness and become winding, so that each side is bordered by a succession of rocky spurs, with tributary valleys running up between them. When looking up such a valley we see a succession of rocky points, one behind the other, running out from either side alternately, and so long as downward corrasion continues these only become more and more accentuated. But when lateral corrasion comes into play the meanders cut into these spurs and remove their ends, so that the final result may be a straight valley bordered on either side by the

truncated ends of these spurs, though this effect is more commonly the result of glaciation, as will appear later.

So long as the conditions remain unaltered a river may continue to increase the width of its meander-belt; and it is possible that the width of this may eventually become so great as to encroach upon the meander-belt of another river, so that their curves intersect. In this case the river which happens to be at the lower level will have the advantage, and will tap the waters of the other. The latter will then forsake the lower part of its own channel, and will be permanently diverted into the other stream. This is one method by which beheading and capture may occur.

Rejuvenation of Rivers. It is not uncommonly observed that the course of a river of evidently ancient date is not a continuous curve from source to mouth, but is broken by one or more rock-steps at certain points of its course. This phenomenon is sometimes explained as due to the existence of a barrier of specially hard rock, through which the river runs steeply in a gorge, but this explanation is not always adequate. The effect can often be accounted for more satisfactorily in another way; namely, by the occurrence of an uplift of the land after the river has reached the base-line proper to the earlier conditions. When such an uplift occurs, the river regains its power of cutting back from its mouth, so that the lower part of its course takes the form of a gradually receding waterfall or series of rapids, while the upper part still maintains its old level. Thus at some point, whose distance from the mouth depends on the date of the uplift, there will be a sudden step in the floor of the valley. If more than one uplift has taken place, there will be a corresponding number of steps. This is one of the methods by which 'hanging valleys' may be formed, this term being used to describe valleys in which there is somewhere a sudden increase of slope; other examples are described in the chapter on glacial denudation.

River Terraces.—Along the courses of many rivers it may be seen that the sides of the valley do not slope up regularly and gradually, but are marked by a succession of steep and almost flat portions. One way in which a single steep bank of this kind may be formed has already been described (p. 56), but a series of them requires some further and less simple explanation. They are usually in fact the result of uplifts of the land, one corresponding to each of the terraces. If such an uplift affects a river with an already established flood-plain, the river will acquire a new power of vertical corrasion and will begin to cut into its own flood-plain, first deepening its bed and eventually meandering again as before. If, as often happens, the new and lower flood-plain is not so wide as the first one, a part of this will be left as a terrace on the sides of the valley, and so on for any number of uplifts. It follows, of course, that the highest terrace must be the oldest and this can often

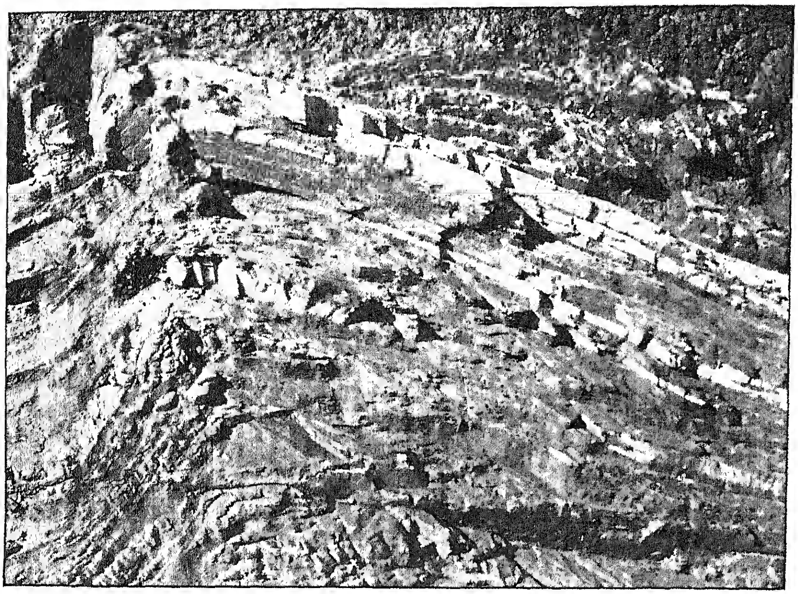
be proved by fossil evidence. The higher terraces of many English rivers contain remains of extinct animals and flint implements of very early types.

Terrace systems of this kind are specially well developed in the Thames Valley, in and around London, where the principal ones are at heights of about 100 and 50 feet respectively, and at Cambridge, where there are also two terraces at about half these heights or a little less.

Let us next consider the case of a river which has already reached its base-line and has established a system of meanders. Then, at a comparatively late stage in its history the region is uplifted, so that the river is again enabled to effect downward corrasion. Such a renewal of the activity of a river may be called *rejuvenation.* Lateral corrasion will then cease or will become comparatively unimportant, and the energy of the stream will be concentrated upon cutting downwards, so that its channel will be sunk below the general surface of the land. But the plan of its course will be preserved, so that the river will flow in a series of meandering curves in a deep valley cut out of a comparatively level high-lying plateau. *Incised meanders* of this kind are an indication of uplift subsequently to the establishment of the base-line of a river. One of the most striking examples is afforded by the deep winding gorge of the Moselle, while in our own country the Wear between Durham and Sunderland flows in a similar valley. The great bend of the river through the city of Durham is a conspicuous feature; it encloses the cathedral and castle on three sides, and to it was due the strategic importance of the city in olden times. Appleby occupies a very similar situation in a great loop of the Eden, and this was also a strong place in very early days.

The Law of Unequal Slopes.—If the uplift which has produced the primary divide of a river was asymmetric, so that the slope on one side is steeper than that on the other, denudation will be more rapid on the steeper side, and the watershed will gradually work back towards the more gentle slope, as is shown in the section in Fig. 38. Here the dotted line represents the original form of the divide, and the unbroken line its form at a later stage. In this case the watershed is receding towards the right: the recession will obviously be most rapid at the heads of the principal streams, so that by this means alone an originally straight divide may assume a zigzag form.

This process is very well illustrated by the streams draining the northern part of the Pennine range, along the Cross Fell escarpment. This escarpment is determined on the west by the great Pennine faults, which have produced a steep slope facing the Eden valley, while the east side consists of a gentle dip-slope of Carboniferous rocks. Consequently the head-waters of the Tees rise close to the edge of the escarpment, and flow eastwards with a very slight fall. On the other hand, the scarp-streams flowing west have a rapid fall, and have excavated deep



F. H. Hatch, photo.

(I) SHARP ANTICLINE: ONE LIMB STEEPER THAN THE OTHER. NKOMO, NATAL.

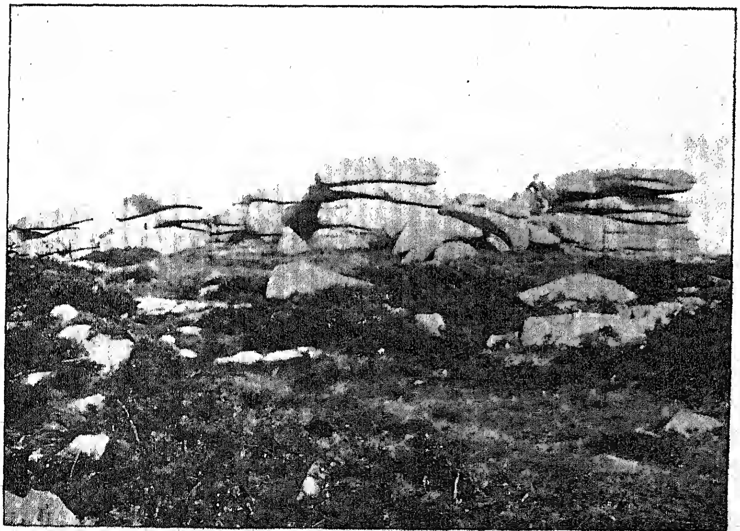
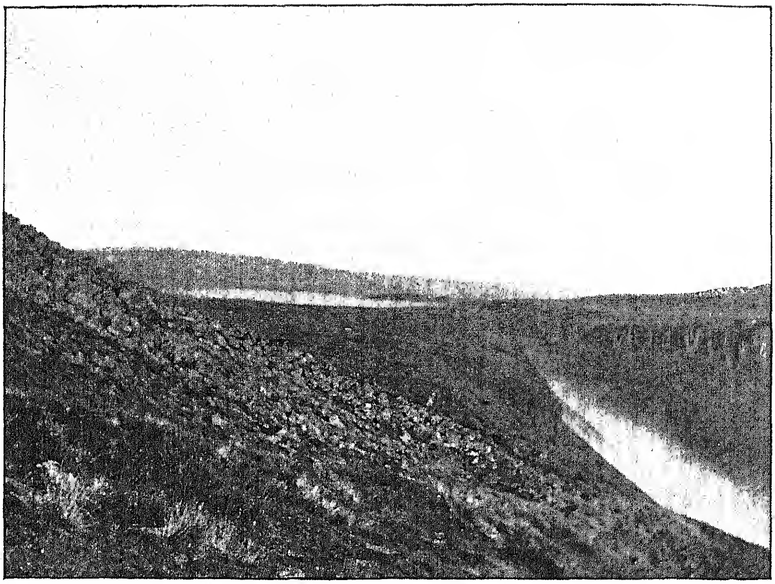


Photo by H.M. Geological Survey.

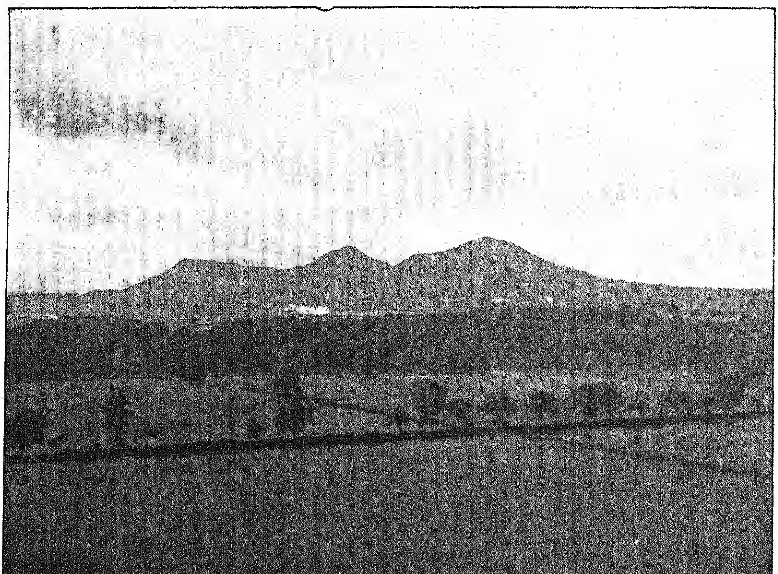
(II) TYPICAL WEATHERING OF GRANITE. CARN BREA, REDRUTH, CORNWALL.

PLATE VIII



E. J. Garwood, photo.

(I) HIGH CUP NICK, AND THE WHIN SILL.



J. Romanes, photo.

(II) RESIDUAL ELEVATION IN A PLAIN OF RIVER EROSION, EILDON HILLS, MELROSE.

valleys. The most striking example is High Cup Gill, near Appleby, which heads far to the east of the highest point of the range, and has cut back into the valley of a tributary of the Tees (Fig. 39).

High Cup Gill runs through a deep gorge into the wide Eden valley. On ascending it and reaching High Cup Nick, at the head of the valley, a broad valley is found, sloping gently down to Maize Beck, a tributary

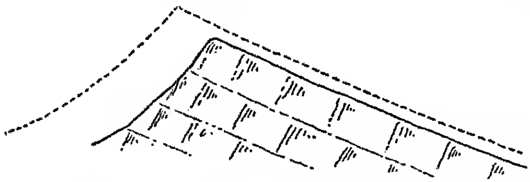


FIG. 38.—RECESSION OF WATERSHED, DUE TO UNEQUAL SLOPES.

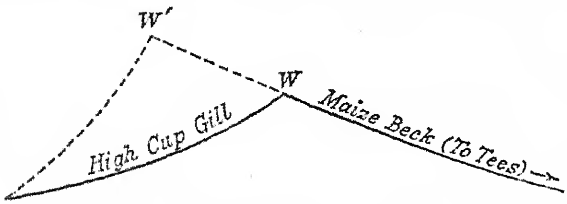


FIG. 39.—DIAGRAMMATIC SECTION THROUGH THE HIGH CUP VALLEY.
W, Present watershed; W′, Ancient watershed. The continuous line shows the present surface, the dotted line the ancient one. (After Marr.)

of the Tees. In this valley a stream runs over the dip-surface of the Tyne Bottom limestone. This valley once extended much further west, but it has been cut into by the High Cup stream and remains of the floor of the old valley can still be seen as a kind of ledge, sloping eastwards, on either side of the head of High Cup Gill (Plate VIII (i)), In the photograph, the distant patch of fog lies in the valley of the Maize Beck, which slopes away from the observer. In time the head of the High Cup valley will recede sufficiently to tap the Maize Beck, and this important stream will be diverted into the Eden drainage, thus depriving the Tees of one of its chief head-waters.

River Mouths; Estuaries and Deltas.—A glance at any atlas will show that rivers end in the sea in many different ways: sometimes in small-scale maps not much is to be made out, especially in the case of small rivers: the valley simply ends in the sea, and there is little more to be said. But in the case of the larger rivers of the world it is not difficult to distinguish two rather extreme and very different types of ending, the *estuary* and the *delta*. Geologically, as well as geographically, these are strongly contrasted, an important difference lying in the kind of deposit formed in them, as will appear more fully in the sections on sedimentary deposits.

It so happens that the British Isles afford three typical examples of estuaries, the mouths of the Thames, Severn and Humber; while on a larger scale the St. Lawrence in Canada is a striking case. The chief characteristic of an estuary is its funnel-shaped plan, the river widening so gradually into the sea that it is quite impossible to say where one stops and the other begins. All estuaries also are necessarily tidal, and this has a most important bearing on the kind of deposit formed therein—since this may bury a mixture of the remains of marine and freshwater or even land animals and plants, and a very characteristic feature is the deposit of masses of mud (river silt) in shallow water. Estuarine deposits are geologically unimportant.

Deltas, on the other hand, are never indentations, but form straight coast-lines or bulge out into the sea: an extreme case of this is the delta of the Mississippi, which projects as long fingers into the Gulf of Mexico. A delta may, however, be a filled-up estuary, as is possible in the case of the Nile. The most striking feature of a typical delta is that the main stream of the river divides up into numerous branches, which wander by meandering over a large area and often change their courses forming a complicated network.

The most typical deltas are formed by rivers subject to periodic violent floods, and this leads to a special type of sedimentation (see p. 91). Their deposits contain remains only of freshwater and terrestrial animals and plants, and are thus easily distinguished from those laid down in estuaries. Delta deposits have been of enormous importance in past ages, since most of our Coal-measures belong to this category.

Consequent and Inconsequent Drainage. In the cases hitherto considered the arrangement and distribution of the river system are directly dependent on the geological structure of the rocks on which it rests, and are a consequence of the uplift of the area. Such a drainage system may be called *consequent*. But there are also cases in which the drainage system does not appear to have any direct relation to the structure of the underlying rocks, but is quite independent of it. Such drainage systems are spoken of as *inconsequent*, and they may be produced in various ways, of which the two following are the most important:—

A. *Antecedent Drainage.*—After the establishment of a complete river system in any given area, and its adjustment to existing conditions, part of the area may undergo uplift, so that a barrier is produced across the course of a stream. The uplift may be so slow that stream erosion can keep pace with it, so that the river is able to saw through the obstruction as it rises, and thus keeps its channel open. The best examples of this process are found in the rivers of Northern India. The Indus and the Brahmaputra both rise on the northern side of the main chain of the Himalayas, through which they cut in great gorges and flow to the Indian Ocean. In this case it is evident that the rivers were in existence before the mountains, which date from a comparatively

late period in the geological history of Asia, viz. from the Miocene. It is impossible to account for their present relations on any other supposition. The rise of the mountain-chain was so slow that the rivers were able to keep open their former channels during an uplift of very many thousands of feet. Since the origin of the rivers was antecedent to that of the principal tectonic features of the district, a drainage system of this type is said to be *antecedent*. A striking example may also be found in Europe. The Danube twice cuts through the Alpine mountain system: once near Vienna, between the Alps proper and the Carpathians, and again at the Iron Gate, between the Transylvanian mountains and the Balkans.

B. *Superimposed Drainage.*—The second case is where the arrangement of a river system has been determined by the structure of a set of rocks on which it was originally formed, but which have been since removed by denudation, so that the rivers now rest on the underlying rocks of different structure. They have completely cut through the rocks which originally determined their distribution, and have settled down on the subjacent strata. Such a drainage system is said to be *superimposed*.

The Drainage of the English Lake District.—A good illustration of superimposed drainage is afforded by the English Lake District (Fig. 40). The central part of this area consists of a mass of highly folded and faulted Lower Palaeozoic rocks, which have a general strike approximately in a N.E.-S.W. direction. This is surrounded by a more or less continuous ring of Carboniferous and newer rocks, which, neglecting minor variations, dip away from the centre in all directions. The whole district may thus be regarded as a denuded dome, from the centre of which the newer rocks have been removed, so as to expose the Palaeozoic core which was folded and faulted before the occurrence of the uplift. The arrangement of the drainage system confirms this view. The dome is not strictly circular, but slightly elongated in an east and west direction, and the rivers take their rise from a short watershed, which runs from the Scafell group in an easterly direction. The arrangement of the principal valleys, in most of which are considerable lakes, is distinctly radial. The upper parts of these valleys lie in Lower Palaeozoic rocks, and there is no relationship observable between the dip and strike of these rocks and the general lie of the valleys, regarded as a whole and apart from local details. But when the streams pass on to the Carboniferous and New Red rocks they become dip-streams or consequents of the ordinary type. It may be concluded, therefore that this drainage system was initiated on the original surface of the dome-shaped uplift, which Dr. Marr believed to have been of Tertiary age, though direct evidence on this point is wanting. In course of time the cover of newer rocks was removed by denudation from the centre of the district, and the streams settled down into, or were imposed upon, the older rocks.

Since this time their courses have undergone slight modifications, owing to peculiarities of structure in the older rocks and the existence of planes of weakness in them. But there is no doubt that the general direction of the main valleys is substantially the same as when the streams were

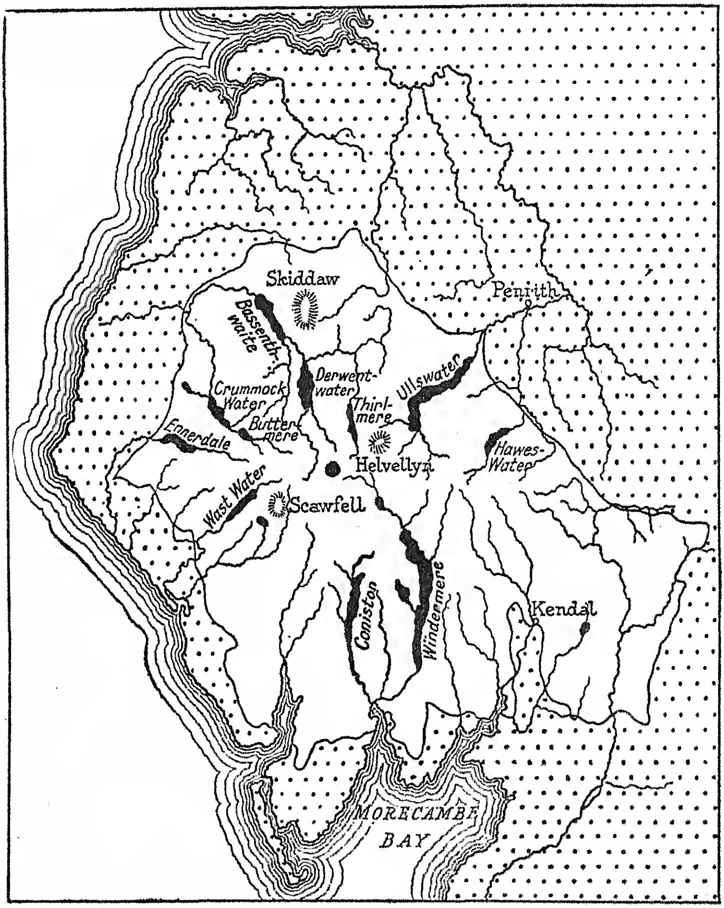


FIG. 40.—MAP OF THE LAKE DISTRICT, SHOWING RADIAL DRAINAGE.

The dotted area represents Carboniferous and Newer Rocks the plain area, Silurian and Ordovician.

first formed, as a consequence of the uplift, and so far as regards the older rocks this is a clear case of superimposed drainage.[1]

It may be useful to point out here that many English rivers have had

[1] Marr, J. E., *The Geology of the Lake District.* Cambridge University Press, 1916, Chapters XIV and XV.

very complicated life-histories, having undergone a great deal of capture and diversion. It is impossible to discuss this matter in detail, but it may be said that many of the more interesting and striking cases are largely due to glaciation: some of these will be mentioned in Chapter VI. The whole subject is discussed in an interesting if somewhat popular way in Chapter XI of Lord Avebury's *Scenery of England* (London, Macmillan, 1903), though not all of the conclusions there set out would now be accepted.

The Influence of Ice on River Erosion.—Many of the large rivers of the northern hemisphere become frozen to a considerable thickness in winter, and it is necessary to take into account the possible influence of this state of things on their geological activity. In Britain the geological effect of river-ice is probably not great, although Lyell long ago pointed out that in the Tay and other rivers pebbles are often carried along by floating ice; and sometimes after a hard winter important changes are brought about on the banks and in the beds of British rivers by a sudden break-up of the ice, especially if, as is commonly the case, the thaw is accompanied by a flood. But to realise the full effects of river-ice we must turn to the colder regions of the globe, such as Siberia, Canada or Alaska. Here the freezing-up of the rivers in winter and their release in spring is a regular annual occurrence, and its powerful effect has long been noticed.

Rocks and boulders partially submerged are often surrounded by large masses of ice, which form round them as a centre. If this mass of ice becomes large in proportion to the mass of the boulder, the buoyancy of the ice may enable it to float off and carry the boulder with it. A process analogous to this occurs in connexion with what is known as *ground-ice*. In many rapidly flowing rivers in cold countries ice forms along the sides and bottom of the channel long before the surface is frozen over. Under the influence of the current masses of this ground-ice or anchor-ice rise to the surface and bring up with them stones of various sizes, which they may transport for long distances. This process seems to be of great importance in many of the rivers of the arctic and sub-arctic zones.

In the case of a river of considerable length flowing from south to north in high latitudes, on the approach of spring the ice will break up first on the upper southern part of the course, and floods of water and half-melted snow, bearing much detritus, will be carried down on to the unmelted ice surface further north. In this way ice-barriers are frequently formed during spring floods, so that the waters are held back and often diverted into new channels. The bursting of such ice-barriers may cause sudden floods, which may produce very well-marked effects, both in the way of transport and corrasion. This phenomenon is well known in the case of several European rivers, notably the Vistula, and causes extensive floods nearly every year in the neighbourhood of

Danzig. This helps to account for the changes that have taken place in historic times in the lower course of that river.

In some highly civilized countries the courses of rivers have been a good deal interfered with by man; hence a map of a small area might be misleading. In the Fenland, for example, the courses of the Nene and Great Ouse have been much altered. The Great Ouse did not originally run by King's Lynn, but wandered off to the N.W. to join the Nene a few miles from Wisbech, and at the present time the so-called Ouse at Ely is in reality almost entirely Cam water: nearly all the Ouse water is carried by two parallel canals, the Bedford Rivers, from Earith to Denver: except in flood-time the flow of the Old West River from Earith to Ely is negligible—while the stretch from Littleport to the junction with the Little Ouse is entirely artificial. The course of the Nene also below Peterborough has been changed several times and is now mostly artificial: the old channel through March being apparently the last wholly natural one.[1]

[1] See *A Scientific Survey of the Cambridge District.* British Association Handbook 1938, especially the map on p. 21 and Chapter XIII.

CHAPTER IV

EARTH SCULPTURE

The Work of Rivers.—It is a self-evident fact that the characters of rivers vary within very wide limits. There is a striking difference between the impetuous torrents of mountain districts, with a swift current of clear water, abounding in rapids and falls, flowing over a rocky bed, and the slow and tortuous streams of the plains, with their sluggish currents of muddy water, bounded by marshy banks of clay and silt. These differences are due to various causes, the principal being the character of the material over which the river flows and the extent to which denudation and deposition have gone on in the district in question. In other words, the topography of any river valley depends on several factors, of which the chief are the hardness of the rocks, the relative age of the river, and the climate. Mountain torrents are young rivers, and the accidents which diversify their courses are due to incomplete denudation, while the rivers of the plains are in an advanced state of development. They have long since established their base-line, and have become completely adjusted to the structure of the country. It must not be forgotten that in such rivers erosion is practically at a standstill. The general level of the surrounding country is not being lowered, and the only corrasion is in a lateral direction. Since the tendency of erosion is to reduce the bed of a river to one uniform curve, the very existence of inequalities, such as falls and rapids, is in itself evidence that the process is incomplete.

It is often not made sufficiently clear that in a region of moderate climate and rainfall, with not very large rivers, practically all the work is done during floods. This is certainly true of the British Isles, though even here a slight qualification is necessary. On the western side the rainfall is so much heavier and more continuous that for long periods at any rate the rivers are always more or less in flood, and therefore much more active than those of the eastern side. It has already been stated that theoretically the carrying power of a river and therefore its capacity for work varies as the sixth power of the velocity and in practice is somewhat less. If we assume that by doubling the velocity the power for work is increased 50 times and by trebling it certainly several hundred times, the marked effect of floods becomes intelligible. Very steep and rapid streams are probably always doing some work, but a river of clear water running over a rocky or gravelly bed of gentle slope at a moderate speed is performing no erosion and very little

transport. It is not until solid matter is visibly moving that anything happens.

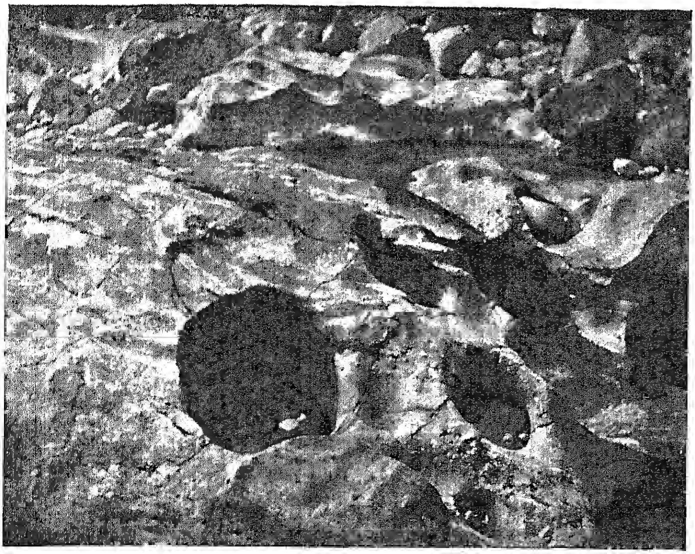
On the other hand, very large rivers draining vast areas are nearly always muddy: hence work must be going on all the time. This means in reality that flood conditions always prevail in some part of the drainage basin: transport is continuous and therefore also erosion and eventual deposition.

It now becomes necessary to consider in some detail the actual mechanism of water erosion in various cases, since there is a good deal of variation in the means employed and the results produced in different circumstances. The most important determining factor is undoubtedly the character of the rock acted on, both as to its composition and its structures. Among other things, in addition to varying hardness, bedding and jointing, or their absence, are of first-class importance.

Pot-holes.—As before stated, slow running rivers carrying no load can do little work. There is, however, one kind of mechanical erosion by such streams that is of importance in deepening river-beds. The flow of a stream is never perfectly uniform, but the velocity varies in different parts, so that differential movements are set up. Inequalities in the bed produce minor currents and eddies which often possess a circular or swirling motion, and these cause a grinding movement of the pebbles on the bottom. Thus hollows of a more or less circular form are produced, and in course of time these may become very pronounced, forming deep holes with curved sides in the solid rock (Plate IX (i)). Such hollows are commonly known as pot-holes, and they are conspicuous features of most streams that flow over a rocky floor. Pot-holes often coalesce, and thus carve away large masses of rock. The formation of pot-holes is often specially marked when a river flows through a lake and is thus deprived of the solid matter in suspension by settlement. This can be well seen in the case of the stream flowing from Watendlath Tarn in the Lake District, which runs for some distance over a rocky barrier. The bed of the stream is carved into a succession of large pot-holes. Other excellent examples occur in the Glens of Antrim in the streams which flow in gorges cut in the edge of the great basalt plateau. The remarkable gorge above Ingleton, in North-west Yorks, seems to have been carved out mainly by the coalescence of many very large pot-holes.[1]

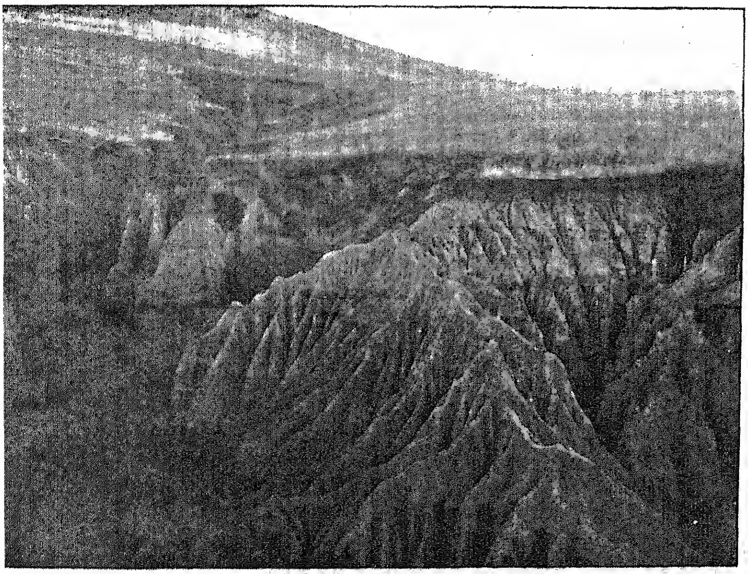
Bad-land Topography.—An erosion-type rarely seen in the British Isles but of great importance in many semi-arid countries is conveniently described by its American name, Bad-land Topography. This may occur on any scale from a few feet to some thousands in height, and it is so called from the difficulty of traversing it. The essential conditions

[1] Another (local) meaning of the word *pot-hole* or *pot* will be found in a later section of this chapter (p. 72).



R. H. Rastall, photo.

(I) POT HOLES. HARTA CORRIE, SKYE.



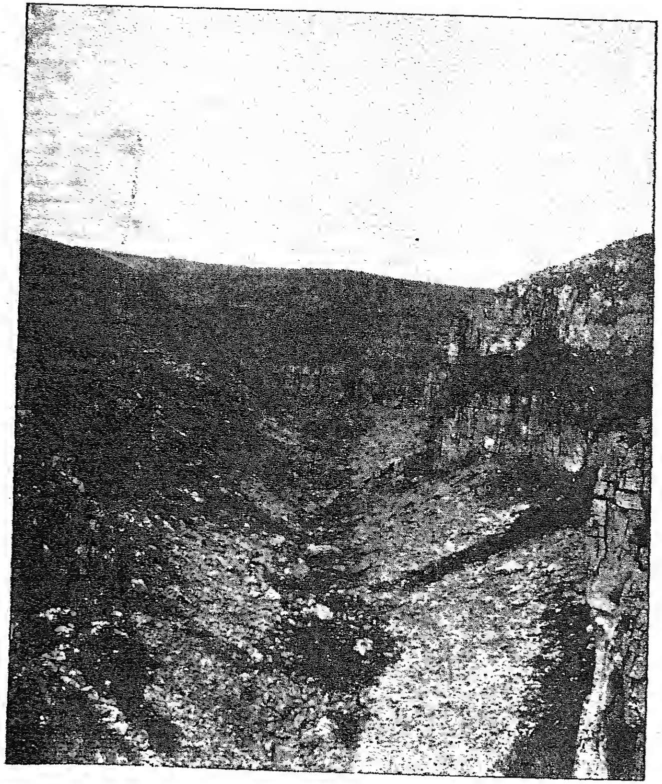
F. H. Hatch, photo.

(II) EARTH SCULPTURE IN HOMOGENEOUS DEPOSIT, NATAL.

PLATE X

J. J. Lister, photo.

(I) GORGE IN LIMESTONE. AARSCHLUCHT, MEIRINGEN, SWITZERLAND.



C. Bingley, photo.

(II) DRY VALLEY IN CARBONIFEROUS LIMESTONE. MALHAM, YORKSHIRE.

are a homogeneous deposit, soft and little cemented, lying flat for some considerable distance and forming the sides of a valley or the edge of a plateau. In such semi-arid regions rainfall, when it does occur, is often violent and in any case the result is that such a deposit when thick is carved into steep faces with a complicated system of gullies and ridges, as seen typically in many of the western states of America. In parts of South Africa again much of the low ground is occupied by great thicknesses of sandy or loamy material, probably formed in an earlier wetter climatic cycle. These are often washed out by sudden storms into narrow, steep-sided gullies, sometimes extending down to solid rock. An example from Natal is shown in Plate IX (ii), which if increased in scale some scores or even hundreds of times would do very well as an illustration of typical American bad-lands. In different countries these small-scale gullies are called nullahs, dongas, and so on. They carry no permanent streams. The nearest approach to bad-land topography in Britain is afforded by some of the cliffs composed of glacial material on the east coast of England.

Earth-pillars.—One of the most striking cases of the dependence of topographic form on rock structure is afforded by the so-called earth-pillars found in certain parts of Scotland and the Tyrol. When the rock is not homogeneous, but consists of large blocks of hard material embedded in a matrix of finer texture, the erosive effect of rain is very unequally distributed. The large blocks act as shields to the finer material below them, which is thus protected from removal, while the material not thus protected is carried away. If the blocks are but sparingly distributed as in boulder clay and in some conglomerates the result is that the large blocks are left standing on the tops of columns of varying height.

Escarpments.—Well-marked topographical and scenic features are often produced when a soft homogeneous flat-lying or gently dipping rock is overlain by a harder massive stratum. In this case the soft rock weathers away more rapidly and the hard rock is left standing up above it, often as a steep or even vertical scarp. Instances of this in cliff-formation will be mentioned in Chapter VIII, but the same effect is seen in many inland localities. Perhaps the best and simplest large-scale example in England is afforded by the Cotswold Hills which consist of the hard limestones of the Middle Jurassic overlying the much softer Lias. Of very similar structure is the north-western and western face of the Cleveland and Hambleton Hills overlooking the plain of Cleveland and the Vale of Mowbray. This is well seen from the L.N.E.R. main line north of York. The great ridge on which Lincoln Minster stands is precisely analogous, the Lincolnshire Limestone overlying the soft Upper Lias. All of these are examples of escarpments carved out of nearly flat-lying rocks. For a more theoretical discussion of the origin of escarpments see page 54.

Dip-Slopes.—If the hard bed as described in the previous section is horizontal a plateau will be formed, but if the rock dips gently and is overlain by another soft stratum, easily removed, the natural concomitant of an escarpment is a long dip-slope, inclined in the opposite direction. These dip-slopes are often the seat of an elaborate river system: for example, the dip-slope of the Cotswolds carries the head-waters of the Thames system. Edge Hill in Warwickshire is an interesting case: here the hard rock is the valuable Marlstone ironstone of the Middle Lias, which extends to the S.E. with little or no cover even beyond Banbury, making the working of the ore cheap and easy.

Plains and Plateaus.—In ordinary language both these words bear the meaning of a large flat surface, but it is difficult to define the difference between them. The commonest idea is that a plain is low and flat, while a plateau is high and flat, but low and high are relative terms. In England a flat surface at 500 feet above the sea would be called high, but in Asia, Africa or America very low. The best solution is to say that a flat surface notably elevated above its surroundings is a plateau, while a flat surface not so elevated is a plain. By this criterion we have in England several plains: the Fenland, the Vale of York and parts of Somerset (Sedgemoor, etc.), but few plateaus; only hill-ranges with escarpments and dip-slopes. Obviously a plateau is the limiting case of a dip-slope, where the dip is zero: hence the Cotswold country, where the dip is very small, is a near approach to a plateau.

Residual Elevations.—When a series of flat-lying strata, consisting of alternate hard and soft beds are undergoing denudation, the lowering of the surface is never uniform: nearly always isolated portions capped by a hard stratum are left outstanding. Geologically these are one type of outliers; geographically various names are applied to them in different countries: *buttes* and *mesas* in America, *kopjes* in South Africa, and so on. As features of this kind are best developed in arid regions the subject will be discussed in more detail in a later section. In America the word *monadnock* (from the name of a conspicuous mountain in New Hampshire) is much used to describe a residual elevation due to almost any cause—while the German expression *Inselberg*, with the same meaning, has acquired considerable currency in English geological literature.

Influence of Joints.—When a rapid stream flows over a surface composed of a well-jointed rock which is not soluble, it can often be seen that the surface does not possess a smooth, uniform curve, but is rather composed of a series of steps parallel to the joint-planes of the rock. In this case it is evident that the rock is not worn away by the grinding of fine particles, but by the breaking off of blocks along the joint-planes. In the general discussion of this subject the term joint should be interpreted in a wide sense, to cover not only true jointing, but also other kinds of divisional planes in rocks, actual or potential, especially

schistosity and cleavage, which have the same practical effect. Related to this is the action of streams on limestone rocks, where the effects of ready solubility are superadded to those of the ordinary processes of mechanical erosion. Solution takes place most readily along joint-planes, which are rapidly enlarged, so that streams in limestone districts tend to run in gorges cut along the major joints. Here the drainage is often underground, in caves and fissures, formed in a similar manner.

There is no doubt that as a determining factor in topographic forms divisional planes in rocks in the broad sense just defined are of the utmost importance. In all or nearly all natural rock faces, except where sculpture by wind action has been prominent, the actual surface is usually some kind of joint face. Rock-falls and land-slips also are often determined by joints. Hard rocks exposed at the surface in steep faces undergo denudation by the falling of joint-blocks rather than by small-scale disintegration. This is proved by the enormous piles of scree material so often seen on steep slopes. The actual summits of mountains are often covered by piles of large blocks, which must have been split up by frost action.

Waterfalls.—When a stream flows over the edges of a series of thick beds of different hardness it often forms waterfalls, which are marked features of many incompletely graded streams. The most favourable conditions for the formation of a waterfall exist when a hard and well-jointed layer overlies one of a softer nature. Such is the origin of the much-described Falls of Niagara, where hard and well-jointed beds of limestone, the equivalent of the well-known Wenlock Limestone of England, overlie a softer shale, representing our Wenlock Shale.

The origin of many British waterfalls is very similar, and as an example we may take High Force in Upper Teesdale. In this part of its course the Tees flows over Lower Carboniferous rocks, chiefly limestones and shales, with a thick bed of intrusive igneous rock, the Great Whin Sill, of somewhat superior hardness. The actual fall is about 70 feet high, and the upper part of the precipice is formed by the Whin Sill, while the lower part consists of more or less metamorphosed limestones and shales. The igneous rock is very well jointed in the form of vertical columns, and, so long ago as 1823, Sedgwick [1] remarked that 'the interest of the scene is greatly heightened by the singular contrast presented by the horizontal beds which form the base, and the prismatic masses of trap which form the crown of the escarpment.' A few miles farther up the valley of the Tees is another well-known fall, Cauldron Snout, also determined by the Whin Sill; and in other parts of the north and west of England are many fine falls whose existence depends on hard beds overlying softer rocks. Of somewhat similar origin are the Falls of Lodore, near the head of Derwentwater. Here the hard volcanic rocks of the Borrowdale series form a steep

[1] *Trans. Cambridge Phil. Soc.*, ii., p. 158.

scarp above the softer Skiddaw Slates, which underlie them and form the floor of the main valley, into which the Lodore stream descends as a tributary.

Much attention has been attracted by the great Victoria Falls on the Zambesi, which were originally discovered by Livingstone. In this case, as at Niagara, the river suddenly plunges from a high tableland into a deep chasm, which is continued as a gorge or canyon for many miles below the falls themselves. By its discoverer and other early writers this gorge was considered to be a crack formed during an earthquake or some other convulsion of nature, but modern research has shown that it is primarily due to water erosion acting on well-jointed rocks.

This region was investigated by A. J. C. Molyneux [1] and by G. W. Lamplugh.[2] The Upper Zambesi flows over part of the high plateau of South Africa, and while at a height of some 3,000 feet it begins a sudden descent over the eastern margin of the plateau, which here consists of a thick series of lava flows, the Batoka basalts. These rocks are well-jointed and are traversed by well-marked lines of fracture, and these two sets of divisional planes together constitute lines of weakness which have materially assisted the erosive action of the river. The chief lines of weakness run east and west, with subsidiary ones at right angles, so that the gorge consists of a series of zigzags having corresponding directions. The chasm at the falls is due to one of these planes of weakness, probably a fault, with a vertical belt of soft, easily eroded veinstuff. The tributary streams below the falls descend into the main gorge by subsidiary falls and gorges having a structure exactly analogous to those of the main river, while above the falls the beds of the tributaries have been graded down to the level of the Zambesi. For some hundreds of miles below the falls the river runs in a series of deep gorges cut through hard rocks, but the angle of slope of the walls gradually decreases, owing to the longer period during which erosion has been able to act, and this affords additional evidence for recession of the falls themselves.

Canyons and Gorges.—The term canyon is popularly used in America to designate a valley of almost any form, but in this country it is most commonly understood to indicate a narrow valley or gorge of great depth in proportion to its width, and having sides of great steepness. The best-known example is, of course, the celebrated canyon of the Colorado : this is perhaps the most remarkable example of river erosion that the world has to show. The conditions of its formation are somewhat peculiar, since the Colorado is one of the very few known examples of a great river cutting through a desert region. Since the action of surface-water and tributaries is practically excluded, the case becomes

[1] *Geogr. Journ.*, xxv., 1905, p. 40.
[2] *Geol. Mag.*, 1905, p. 529; *Quart. Journ. Geol. Soc.*, 1907, p. 162.

comparatively simple, as we have only to consider the action of the main stream.

The Grand Canyon of the Colorado is some 300 miles long, and has a maximum depth of about 6,000 feet. When regarded in cross-section it is seen to consist of two parts: a wide upper valley having a total breadth of about ten miles, with a flat floor and sides of moderate slope, and an inner part, the canyon proper, which is very narrow and has walls in places approaching the perpendicular. It is considered that the upper, wide part was formed during a period of more normal climatic conditions than those now prevailing: it is, in fact, a river valley of very ordinary type, due to water erosion and planation. After a time the climate changed, local rainfall practically ceased, and the river began to cut exclusively downwards. In spite of its vast size, it is quite evident that the Colorado canyon is a young valley, in which the processes of denudation are very incomplete. Canyons on a large scale also occur on the Yellowstone, the Snake River, and many other rivers of the western United States.

Although in Britain we possess no canyons on the stupendous scale of these American examples, yet there are to be found cases of deep and narrow valleys which merit the name of gorges. One of the best known of these is the Cheddar Gorge in the Mendip Hills in Somerset. This gorge, whose maximum depth is about 420 feet, has been cut in beds of well-joined Carboniferous limestone, which dip south at about 20°. On the southern side the cliffs are nearly vertical, while on the northern side the slope is more gradual and often coincides for a short distance with the dip of the limestone. For the greater part of its length the gorge is now dry, but near its lower end a stream issues from the rock. As regards its manner of formation, it has been suggested that the gorge is due, in the main, to the subterranean action of water, which, by enlarging fissures, gave rise to a cave, whose roof eventually fell in.

Many of the most remarkable gorges in Britain are due to special circumstances, viz. to glacial action. Many of the preglacial valleys of Britain appear to have been filled up by ice or drift material, or both, so that the streams were forced to carve out new channels for themselves; these new channels often possess characters very different from those of the old valleys (cp. Plate X (i)). We shall return to this subject in a future chapter.

Denudation in Limestone Districts.—In many limestone districts there is developed a peculiar type of topography which merits special description. The weathering of limestone differs, in some important respects, from that of other rocks; and this difference is due to two principal causes, viz. the solubility of calcium carbonate in natural waters, and the highly developed system of joints nearly always found in such rocks. As a result of these two causes taken together, the greater part of the water circulation in limestone regions is under

ordinary conditions underground, and this leads to the formation of fissures and caverns, often on an enormous scale.

When rain-water falls on a well-jointed surface of limestone it soon runs into a joint-fissure. Here the action of solution comes into play, and the joint is rapidly enlarged. A constant stream of water falling down a fissure of this kind will eventually produce a funnel-shaped or cylindrical shaft, often leading down to a great depth. Such structures are well seen in the Carboniferous Limestone district of North-west England, especially in the area to the north of Settle along the valley of the Ribble. It is found that, on the whole, the flow of underground water in limestone rocks follows the direction of the major joints; but some deviations from this rule occur. A study of the development of such a system shows that as soon as a channel sufficiently large to admit of a free flow of water is formed by solution a number of other factors come into play, which tend to modify the original direction. If the rocks are inclined, erosion is stronger on the downward side, so that the stream cuts sideways. When there are cross-joints the dip may produce a lateral escape along these, so as to give rise to a zigzag course. Up to a certain point erosion is entirely by solution, but as soon as the external opening becomes large enough to admit sand and gravel, mechanical erosion begins. This rounds off the sharp angles of the zigzags and produces a meandering course. As the size of the channels increases there appears to be a tendency to simplification and straightening, and deserted channels often exist. Among the most remarkable features of this region are the vertical shafts or swallow-holes: the largest of these is Gaping Ghyll, which is 365 feet deep. At the bottom of the shaft is an enormous chamber, 480 feet long, 80 feet broad, and 110 feet high. The underground circulation of water in this neighbourhood is very complex, and some remarkable features occur. In one case a stream which falls down a swallow-hole reappears as a spring on the other side of the Ribble, 12 feet above the level of the water in the river. Many of these swallow-holes are locally known as 'pots' or pot-holes: this term must not be confused with the pot-holes formed in the bed of a river, as described on p. 66.

The absence of surface water has a peculiar effect on topography, since it causes limestone to behave as if it were a hard rock, and to form conspicuous plateaus, which are often bounded by a steep escarpment. The formation of these dry, rocky plateaus is a characteristic feature of almost all limestone districts. In this country they are specially well developed in the Carboniferous area of West Yorkshire, around the head-waters of the Ribble. The bare surfaces of the limestone are locally known as 'clints.' A good example of such a plateau is afforded by Ingleborough. The middle platform of this mountain consists of the thick limestones of the Lower Carboniferous series surmounted by a mass of Yoredale rocks, chiefly shales and grits, forming

the higher slopes, with a capping of Millstone Grit on the summit. The surface of the plateau presents a very peculiar appearance: the limestone is so pure that there is no soil, and the whole consists of a bare and corrugated surface of smooth rock, with innumerable joint-fissures, in which ferns and other shade-loving plants grow luxuriantly. These fissures are locally called *grikes*.

Dry Valleys.—The character of the drainage systems of these limestone districts, both above and underground, shows that at one time the volume of drainage water must have been much greater than at present. Almost everywhere there are to be found large and deep valleys, now entirely streamless or only occupied by temporary streams during periods of unusually heavy rainfall, but showing indications of having been eroded by subaerial denudation of the usual type. A good example is the dry valley which extends from a little below Malham Tarn to the top of Malham Cove, at the head of Airedale (Plate X (ii)). Some of the valleys of the Mendips are very similar to this. It may indeed be said that dry valleys occur in almost all districts where calcareous rocks are dominant, and they are common even in the Chalk. The probability is that these valleys were formed during a period of heavy precipitation, either during or just after the Glacial Period; and the idea has been put forward that some of them, at any rate, were formed while the rocks and soil were actually frozen, so that water falling on the surface was not able to penetrate downwards in the usual manner.

On the eastern side of the Adriatic, in Carinthia, Carniola and Istria, is a vast spread of dolomite-rock, which presents all the features here described in a remarkable degree, and on a much larger scale than in Britain. This region is locally known as the Karst. The great plateaus of Jurassic limestone in the south-east of France, in the neighbourhood of Montpellier, are very similar.

Caves.—Incidental references have already been made to the common occurrence of caves in limestone regions; and it may be stated that they are almost restricted to this class of rock, since no other possesses in such a high degree the requisite characters, viz. well-developed joints and high solubility. The formation of caves is, in fact, very closely connected with the underground circulation of water just described, and caves or caverns, using the term in its popular sense, are only unusually large channels formed by underground circulation and denudation. The best-known caves in Britain are those of the Mendip Hills in Somerset, the Peak district in Derbyshire, and the neighbourhood of Settle and Ingleton in North-west Yorkshire. Caves are sometimes simple, consisting of one chamber only; but more commonly there are several chambers, communicating with one another by means of narrower passages, often of the most complex nature. As would naturally be expected, these narrow passages generally run along the

joint-planes of the rock, so that the whole system has a more or less rectangular arrangement. This peculiarity shows itself both in the horizontal and vertical planes, hence many caves consist of a series of chambers one behind the other in a step-like manner, with a general downward slope towards the entrance. The connecting passages are frequently vertical or nearly so.

Many caves present features of great palaeontological and archaeological interest, since they have served as dwelling-places for many animals and for man, and traces of their occupation are often well preserved in deposits afterwards formed.

Cave Deposits: Stalactites and Stalagmites.—The water which circulates through limestone rocks is always peculiarly rich in dissolved carbonate of lime, and when this water drips from the roof a certain proportion of it is evaporated, and the carbonate is deposited either on the floor or on the roof of the cave. It often forms most beautiful incrustations or long pendent structures like icicles. When these hang from the roof they are called stalactites, and similar cone-like masses on the floors are called stalagmites. When the deposit shows no particular form, it is generally spoken of as calc-sinter or travertine, or sometimes as calcareous tufa. Besides these chemical deposits, caves often contain great accumulations of mechanical sediment carried in by streams, especially during times of flood.

Underground Circulation of Water.—One of the most important applications of geology to practical problems is in connexion with water-supply. This subject is intimately connected with geological structure, and is of considerable complexity, so that it is only possible here to give a brief outline of the leading principles.

When rain falls on the surface of the land there are three courses open to it: it may evaporate; or run off at once, ultimately to unite into runnels, streams and rivers; or it may to a greater or less extent penetrate into the rocks. Probably it always penetrates to some extent, so that the exterior portions of the earth's crust always contain a good deal of water. The downward extension of this ground-water varies widely in different places, being dependent not only on climate, but also on the porosity of the rocks and the presence or absence of open fissures, such as joints and fault-fissures. Most borings of moderate depth and shallow mines show abundance of water, but really deep mines are often quite dry, unless definite fractures happen to be specially large and numerous. Further, there is a limit to the depth at which openings of more than capillary size can exist, since rocks under very high pressures behave as plastic material. In any case, the downward limit of ground-water is usually vague and ill-defined. For our present purpose this is of no practical importance, and we have to deal only with the conception of a region at a certain depth saturated with water, and possessing a more or less definite upper surface, above which the

rocks are not saturated. This upper level of saturation, or *water-table*, is of the utmost importance in practical questions of water-supply, since its position is directly dependent upon geological structure, and is the controlling factor in determining the occurrence of springs and in fixing the position of artificial wells.

In regions possessing an abnormally dry climate the relations of underground water are peculiar, as explained later; but in temperate regions it may be said that more water always falls on the surface and percolates downwards than is required to maintain the saturation of the ground-water belt. Consequently, the upper limit of this belt tends to rise, and would do so continuously were it not that the water is usually drained off and kept at a constant level by outflow in the form of springs. Where the geological structure is suitable, the water-level may reach the surface, or even extend above it, forming marshes, swamps or lakes; here the water accumulates until it is enabled to find an outflow in the usual manner, or until a change of climate lowers the level of saturation below the surface. Thus it will be seen that the position of the upper limit of saturation is a function of many variables.

Origin of Springs.—The permeability of rocks to water is very variable, and depends largely on the composition and texture of the rock. Water naturally penetrates much less easily into a close-grained, compact substance like clay than into a porous rock like sandstone, or into a well-jointed limestone. A distinction must here be drawn between rocks which are actually porous, like gravels and coarse sands and sandstones, and those which are close-grained and dense, but are traversed by numerous open joints or other planes of division, so that they can hold water in the open spaces and allow it to circulate. In rocks of the last-named category, water travels much more quickly than in the continuous but porous types. If the pores are very small, capillarity acts so strongly that the water can move only very slowly, or in extreme cases not at all.

We thus arrive at a threefold classification:[1] (*a*) Rocks that are both porous and permeable—e.g., sand, gravel, breccia, sandstone, chalk, oolitic limestone, dolomite, brown ironstone and weathered rocks in general. (*b*) Rocks holding water in open spaces—e.g., quartzite, grit, conglomerate, limestone, most igneous and metamorphic rocks, when jointed. (*c*) Impervious rocks—e.g., clay, shale, marl, brick-earth, also slate and most igneous and metamorphic rocks, when not jointed.

The distribution and mutual relations of masses of permeable and impermeable rocks, stratified and unstratified, are the principal determining factors in the circulation of underground waters and the distribution of natural springs. They are also of great practical

[1] H. B. Woodward, *The Geology of Water-Supply* (London: Arnold, 1910), p. 19.

importance in choosing sites for artificial wells and borings. The principles involved can be best illustrated by a few examples.

The simplest case is where a tract of country consists of a mass of permeable strata overlying impermeable ones. Here the ground-water will accumulate in the lower part of the permeable rocks, and wherever denudation has trenched the land deeply enough to expose the junction of the two series, springs will issue (Fig. 41). The upper surface of the

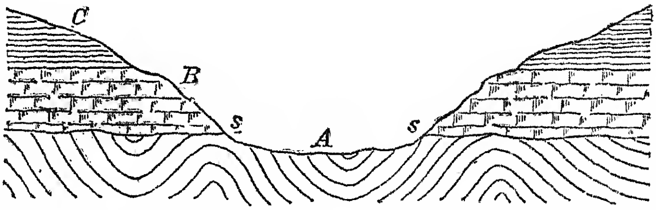


FIG. 41.—DIAGRAMMATIC SECTION TO SHOW THE RELATIONS OF THE OLDER AND NEWER ROCKS IN WEST YORKSHIRE, WITH SPRINGS ISSUING ALONG THE UNCONFORMITY.

A, Highly folded, impervious Lower Palaeozoic rocks; *B*, Carboniferous Limestone; *C*, Yoredale Shales, etc.; *s*, *s*, Springs.

ground-water is found to be not horizontal, but to follow more or less closely the contour of the ground. This is due chiefly to the hindrances to free flow within the rocks themselves, owing to friction and capillarity. This state of affairs is well illustrated by some of the valleys in the Ingleton district in West Yorkshire, where porous Carboniferous Limestone rests on the massive slates and grits of the Silurian and older formations. On the limestone there is hardly any surface flow of water;

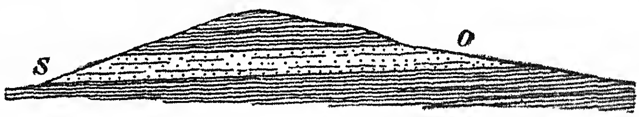


FIG. 42.

The spring, *S*, rises at a point far from the outcrop, *O*, which supplies it with water.

all the rain sinks down joint-fissures and circulates underground. When it reaches the Palaeozoic floor its further descent is prevented, and copious springs issue on the sides of the valleys which have been eroded deeply enough to expose the older rocks. Although the actual junction is commonly concealed by drift or alluvium, it can be followed on the ground with the greatest accuracy by means of the line of springs issuing from it. An almost exactly similar state of affairs exists in southern and eastern England, where the Chalk rests on the impervious

clays of the Gault, or on the Chalk Marl, as in the neighbourhood of Cambridge.

If a pervious water-bearing stratum lies between two impervious ones, the water which falls upon the outcrop of the former will follow its underground course, and may issue as springs in a locality far removed from where it fell, as shown in Fig. 42. The number of possible variations of arrangement in connexion with water-bearing strata and springs of this kind is almost infinite, and no good purpose would be served by discussing them in detail. One important case, however, deserves mention, where the continuity of the strata is interrupted by a fault, so that a mass of impervious rock is brought up against a pervious one, as shown in Fig. 43. Here a kind of natural reservoir is formed, and springs will issue along the line of the fault.

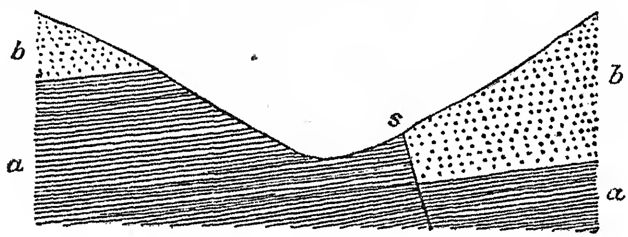


FIG. 43.—FORMATION OF A SPRING BY A FAULT.
a, Impervious; *b*, Pervious strata; *S*, Spring.

Artesian Wells.—One of the most important questions connected with water-supply, both from the scientific and economic standpoint, is the possibility of obtaining water from deep-lying strata. For all purposes this is much to be preferred to water from shallow wells and springs, owing to its freedom from contamination. The most favourable conditions for artesian wells and deep borings for water are found where a water-bearing stratum is enclosed between two impervious ones, and the whole folded into a synclinal form. The water falling on the outcrop of the pervious stratum runs into the synclinal basin, and is there stored under the pressure of a large head of water. Consequently, if the upper stratum is pierced by a boring, the water will be forced out under pressure, and may even form a jet rising high above ground-level. These conditions are almost ideally realised in the London Basin (Fig. 44). The water-bearing stratum, the Chalk, lies between the London Clay above and the clays and marls of the Gault, etc., below. The Chalk has a wide exposure in the North Downs to the south, and the Chalk hills of Bucks, Beds, Herts, and Cambs to the north. The rain which falls in these latter districts is nearly all absorbed, since there is hardly any surface drainage in Chalk districts; and it accumulates below London under a pressure equal to the weight

of a column of water whose height is the difference in level between the tops of the Chalk Hills and the base of the London Clay. Of course, in reality the effective pressure is much less than this, being enormously reduced by friction; but still it is sufficient to cause the water to rise freely to the surface in such wells, or at least it did so in the case of the earlier ones. Owing to the increasing number of deep wells, pressure is now much reduced, and recourse must generally be had to pumping.

There exist in the town of Cambridge many deep wells, in which the general principle is the same as that just described. Here the water-bearing stratum is the Lower Greensand, which yields specially good water. Its outcrop is about four miles west of Cambridge, and the dip is very gently to the south-east, so that underneath the town the Lower

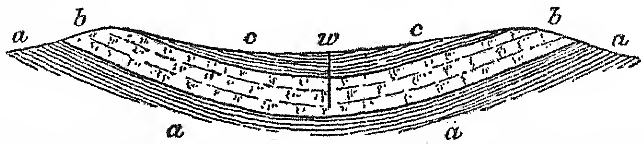


FIG. 44.—DIAGRAMMATIC SECTION ACROSS THE LONDON BASIN, SHOWING CONDITIONS FAVOURABLE FOR ARTESIAN WELLS.
a, a, Gault (impervious); *b, b,* Chalk (pervious); *c,* London Clay (impervious); *W,* Well.

Greensand lies at a depth of about 130 feet. It rests on the impervious clays of the Upper Jurassic, and is overlain by the equally impervious Gault. Consequently, if a well is sunk 130 feet or more, water will tend to rise in it. Here also, owing to the number of wells, the pressure is now much reduced.

It will be seen that the structure just described is in reality half of an artesian basin: it is not known how or where the Greensand ends off to the south-east, but it is obviously water-tight in that direction. A structure of this kind is conveniently called an *artesian Slope.*[1]

Mineral Springs.—This term is applied in popular phraseology to springs which contain sufficient mineral matter in solution to give a distinct taste to the water. The term is therefore very vague, since a spring may hold in solution a large amount of a tasteless compound, such as calcium carbonate, and yet it would not be called a mineral spring, while the presence of a very small proportion of magnesium salts or sulphuretted hydrogen would give a decided flavour to the water. The term is most commonly applied to such springs as have, or are believed to have, medicinal properties. Saline springs contain compounds, especially chlorides, of sodium, potassium and magnesium;

[1] For an admirable summary of the whole subject see Bernard Smith, *Geological Aspects of Underground Water Supplies,* a reprint of lectures given to the Royal Society of Arts, London, 1936.

sulphur springs contain compounds of sulphur, especially sulphuretted hydrogen. This is usually derived from the decomposition of mineral sulphides in the rocks through which the water has flowed: some sulphur springs are of volcanic (solfataric) origin. Chalybeate springs are those rich in compounds of iron. Speaking generally, it may be said that the mineral constituents of spring water are derived by solution from the rocks through which the water has percolated, and its character naturally depends on the prevailing soluble compound in these rocks. Some springs issue at a temperature at or near that of the air; some are colder, especially when of fairly deep origin, while others are distinctly hotter than the air or ground temperature. Hot springs are known whose temperatures range up to boiling-point, and these are described in the chapter on Vulcanicity. The temperature of springs of deep origin is often very constant, being at or near the invariable ground temperature, so that they appear cool in summer and warm in winter.

There is only one hot spring in England, at Bath, but that is a remarkable one. The actual temperature of the water is about 120° F. and the yield about 400,000 gallons a day. The water is saline and distinctly radio-active. Since Bath is far removed from any volcanic region, the high temperature is suggestive of a very deep-seated origin, and the same is true of some high-temperature springs in the Worcester district of Cape Colony. Most of the famous hot springs of Europe are in or near regions where vulcanicity has been active in comparatively recent geological times and they will be mentioned in the chapter on that subject.

Denudation in Arid Regions.—It has already been mentioned that in arid regions the topographic forms are often peculiar and characteristic, differing considerably from the results produced under more humid conditions. Yet it is not altogether easy to account for the differences. Probably presence or absence of vegetation has a good deal to do with it. Abundant vegetation is certainly protective, as is clearly proved by the rapid denudation that follows the clearance of forests even on quite low ground.

According to the usual American classification any region with less than 10 inches of rainfall is arid, and between 10 and 20 inches semi-arid, but much depends also on temperature so far as vegetation is concerned. With a very hot climate more rain is necessary for plants. It is of some interest in this connexion that parts of eastern England which are quite fertile have a rainfall very little above the semi-arid limit just given (e.g. Cambridge 21 inches, and parts of Essex under 20: average of 80 years). Before there was any extensive tree-planting there certainly was a strong likeness between the Breckland of Norfolk and Suffolk and parts of the southern Transvaal.

Some of the most characteristic features of arid and semi-arid

regions, especially if composed of horizontal strata varying in hardness, are the formation of plateaus, often cut by steepsided gorges; and in a more advanced stage of erosion, isolated residual elevations, buttes, mesas, kopjes and so on, as before described. The essentials for this type of landscape are occasional well-defined bands of harder rock to act as a cap, and some rainfall, but not too much. From what has already been said earlier in this chapter the actual manner of formation of such features will be obvious, and need not be described further.

In true deserts, however, where there is little or no rain, the only important weathering agents are changes of temperature and strong solutions brought up by capillarity. These lead to a rapid and deep-seated breaking up of the rocks, and provide vast quantities of dry, finely divided material to be acted on by agents of transport. Besides gravity, the only transporting agent of general importance is wind: water action is rare and local. It is true that on occasion great effects may be brought about by the sudden and violent rainstorms commonly spoken of as 'cloud-bursts,' but compared to the total amount of erosion these are probably insignificant, though occasionally very striking effects are produced over limited areas.

The study of desert erosion begins most conveniently with what are known as rock-deserts. These consist of great expanses of bare rock, usually of a mountainous nature, and here processes of denudation have full play. The sand formed by weathering is carried away by wind, and tends to accumulate at lower levels and to fill up inequalities in the ground, so that the final stage of such denudation is the production of a level plain. The higher ground is destroyed by erosion, and the hollows filled up by sedimentation, and after an intermediate stage of hill and valley we finally arrive at the vast almost level plain of sand, the popular idea of the desert.

It is in the intermediate stages of this process that the most interesting phenomena are observed. Chemical weathering often extends very deeply, and in an apparently capricious manner; it is facilitated by heavy dew, especially on the shady side of projecting rocks and cliff faces, and as a consequence curious hollows are produced, and a rock may sometimes be worn away to a mere shell. This kind of weathering, in conjunction with the scaling off of flakes from the surface (*desquamation* of Richthofen), often leads to very remarkable results. A mass of projecting rock is often weathered into the semblance of a wall with rows of windows and a continuous hollow passage behind, or rows of rock-pillars, columns and needles may be formed. All this appears to be due to intensive weathering along regular joint-planes. When this sort of action is combined with undercutting by blown sand very remarkable forms may be produced, such as mushroom-shaped rocks, often with a fringe of needles projecting downwards from their under surface.

The production of rock-pillars and mushroom rocks is not confined to desert regions. Even in England examples are known, such as the Brimham Rocks near Harrogate, the Hemlock Stone at Stapleford in Notts, and some very good examples in the Calcareous Grit of the East Yorkshire moors (Plate XI (i)).

On level ground there is often little or no evidence of a general lowering of the surface, except where there are alternate beds of hard and soft rock, such as limestone and shale. Channels are cut by weathering and the sand-blast along the joints of the limestone down into the shale (see Fig. 45). These fissures are shaded, and chemical weathering

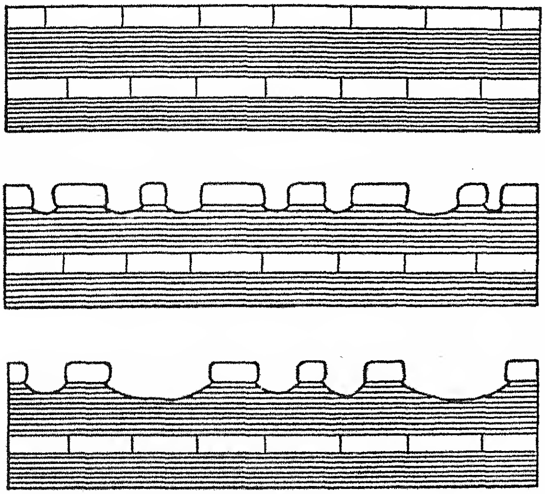


FIG. 45.—STAGES IN THE FORMATION OF ZEUGEN.

proceeds freely, so that the limestone bed is undercut. Thus tables and pillars are formed with a cap of limestone on a support of shale. Eventually the caps fall off, and the shale is then rapidly weathered down to the next hard band, and so the whole process is repeated. These stratified masses projecting above the general plane surface are called *Zeugen*, and they are found of all sizes, up to 100 feet or more in height. All these and similar phenomena are well seen in parts of the Libyan and Arabian deserts, and along the Red Sea.

The Sahara.—As an example of a typical desert we may take the Sahara. This area is by no means uniform, and a study of it by Zittel, Walther and others has led to a recognition of several more or less clearly defined types of desert topography. Contrary to the commonly received opinion, the Sahara is not a vast low-lying level plain or basin, but it is essentially a plateau or series of plateaus several hundreds or even thousands of feet above the sea, and only one or two very limited

areas at the eastern end are below sea-level. There are one or two isolated mountain-chains composed of disturbed rocks, but almost the whole area consists of horizontal strata. The essential structure of the Sahara is that of a series of terraces or plateaus, rising one above the other and bounded by steep cliffs. These cliffs are a prominent feature, and it is on them that the peculiar erosion-forms before described are specially developed. They are usually bordered by a conspicuous girdle of Zeugen of varying size, and they also show rock walls with windows, rows of pillars and other peculiar forms.

As regards the form and character of the ground, four chief types are recognized by Zittel—

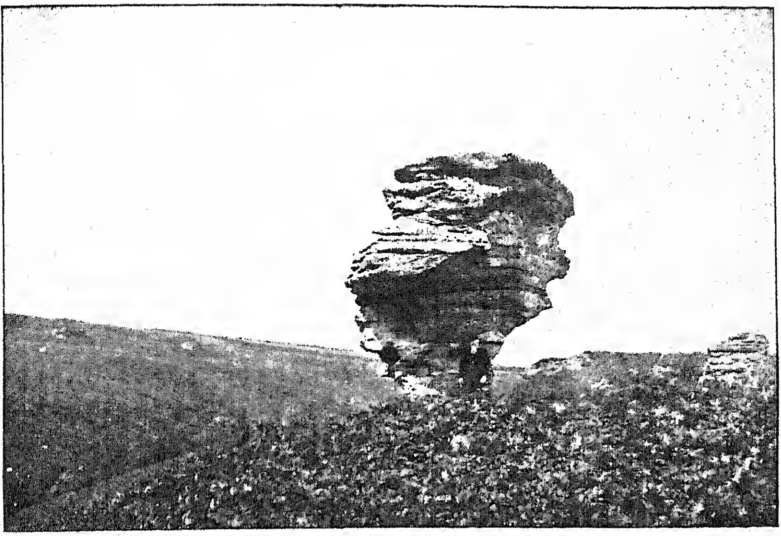
1. Plateau desert, or Hamâda.
2. Erosion desert.
3. Sand desert.
4. Mountain desert.

Of these, the first is the most widespread. It is the desert in the true sense,—the hard surface of a plain without noticeable elevations or depressions, without water or vegetation. The surface consists of bare rock or of hard loamy soil covered with rock-fragments.

The second division, or erosion desert, includes the most remarkable forms of weathering and erosion; it possesses a highly diversified surface, and includes the bounding walls of the plateaus with their Zeugen and Wadys. Besides valleys of the Wady type, which are more or less similar to ordinary river-valleys, there are also to be found great hollows, often called *Schotts*. These are sometimes completely dry, and sometimes contain salt lakes. When a certain amount of water is constantly to be found, and the ground is not too strongly impregnated with salt, these depressions form *oases* which are sometimes marvellously fertile. In many of them are copious springs, which issue at a high temperature up to 105° F. The water from these springs is, however, all removed by evaporation and transpiration of plants, and none of it reaches the sea. In many parts of the Sahara underground water is abundant; new oases have been established in Southern Algeria by the French engineers, by means of deep borings and artesian wells, and much new ground has been brought under cultivation.

Sand or dune deserts are the most desolate of all; they show a single vast sea of sand, of a white or yellowish colour, often mixed with gypsum. The surface is by no means level, but is broken up into great sand-dunes from 50 to 400 feet high, and sometimes between these the rocky floor is exposed. The structure and origin of sand-dunes is discussed elsewhere, under the heading of Terrestrial Deposits (see p. 27).

In the central and higher parts of the Sahara the Hamâda type passes into mountain desert: the highest plateaus reach as much as 6,000 feet above sea-level, and they are dissected by erosion into marvellously

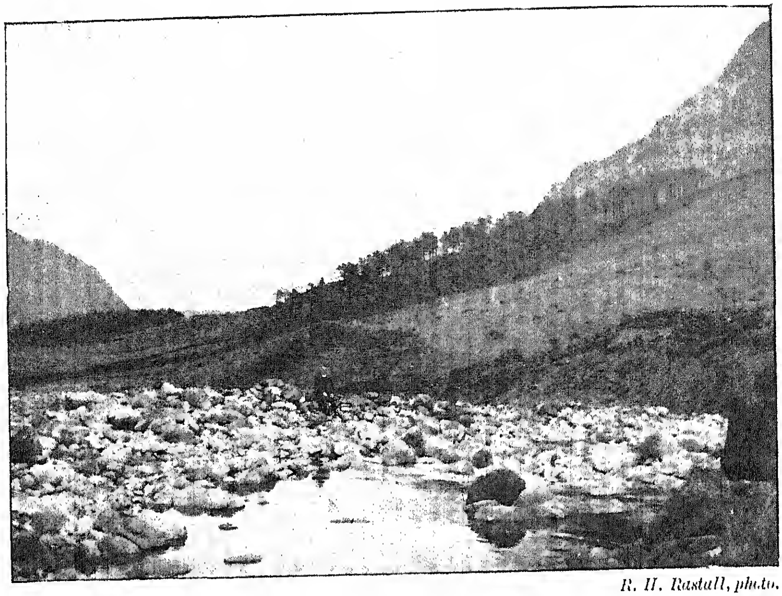


Miss M. Keighley, photo.

(I) THE BRIDE STONE, NEAR PICKERING, YORKSHIRE.

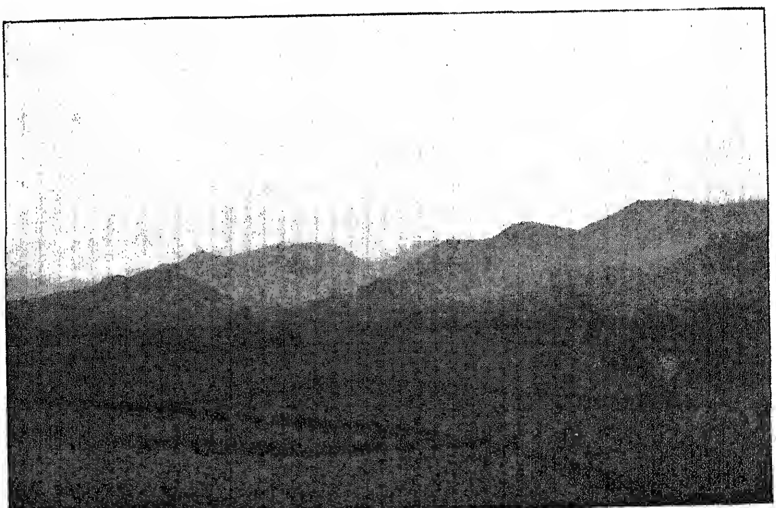
(II) THE SPHINX, GHIZEH, EGYPT, SHOWING THE ORIGINAL FALSE BEDDING OF THE SANDSTONE AND THE ROUNDING AND ETCHING PRODUCED BY WIND-BLOWN SAND.

PLATE XII



R. H. Rastall, photo.

(I) TORRENTIAL STREAM DEPOSIT, SEATHWAITE, CUMBERLAND.



R. H. Rastall, photo.

(II) ALLUVIAL FLAT, BETWEEN DERWENTWATER AND BASSENTHWAITE LAKE, CUMBERLAND.

complex forms, of essentially the same type as those of the erosion deserts already described, but on a larger scale.

Wind Erosion and Transport.—After the rock-material has been disintegrated by weathering, in the manner previously described, by high temperatures and chemical action, the further processes of erosion are almost entirely performed by wind. It is true that there is occasionally, even in the driest climates, violent local action due to cloud-bursts and torrential rains, but, compared to the whole amount of denudation performed, this is insignificant. In the more hilly regions streams arise and carve out valleys for themselves for a certain distance, but they are soon lost by evaporation and the porosity of the ground.

Erosion by wind divides itself naturally into two parts—removal of material or *deflation*, which, of course, comes under the heading of transport, and actual corrasion or wearing away of the rocks by the dynamical effect of moving sand.

As above pointed out, deflation is the active agent of transport, and practically the only one; in conjunction with a special type of weathering, it is responsible for the peculiar relief of the desert. The action is very simple, so much so that there is really little to be said about it: it consists in removal of loose material from exposed surfaces, its transport for a greater or less distance according to circumstances, and its final deposition, usually in a hollow or at a low level. In many regions wind-blown sand exists chiefly in the form of dunes or wave-like masses, whose form is determined chiefly by the effect of obstructions on air-currents. This subject is dealt with elsewhere.

Another point worthy of notice is that, unlike most agents of transport, wind can carry material uphill, and also across water-surfaces. Sand and dust from the Sahara are often carried by southerly winds into Sicily and other parts of Southern Europe. Very commonly also sand and dust are carried in large quantities into the salt lakes of desert regions and choke them up with deposits, which eventually solidify into sandstone and marl, and may frequently be interstratified with beds of rock-salt, gypsum and other soluble salts.

It appears that the maximum diameter of sand-grains commonly removed by ordinary winds is about 2 mm., but during storms particles of much larger size are carried up into the air, and when they strike the surface of rocks they have very considerable energy.

However, according to the best authorities, erosion by blown sand is of much less importance than is commonly supposed. As compared with the effects of weathering and deflation, it is likened by Walther to a small decoration on the front of a great building. It is everywhere observable, but its power is much over-estimated.

The general effect of the *sand-blast* is to produce a conspicuous rounding and polishing of surfaces exposed to it. It brings out differences of hardness in stratified rocks, it digs out the felspar crystals from porphy-

ritic lavas, and causes concretions and hard fossils to stand out as projections. However, in the case of fossils in particular, all finer details are generally lost, since the surface is usually much smoothed and rounded. Unlike glaciated rocks, wind-polished surfaces never show scratches. The effect of the sand-blast on exposed pebbles lying on the ground is peculiar; they are polished by the sand-blast and are worn into smooth faces, which tend to enlarge and give a facetted appearance. These facetted faces eventually meet in straight edges, and from their prevailing three-cornered form these pebbles are known as *Dreikanter*. The edge between two facets is parallel to the direction of the air-currents along the ground, but does not necessarily coincide with the direction of the prevailing wind, as commonly stated, since local deviations may arise from many causes.

The occurrence of Dreikanter is of great geological importance, since in conjunction with wind-polish they form an indicator of the former existence of wind action.

Although its geological effects are small and rather superficial, the sand-blast is actually an agency of great power. Some instances of this are quoted by Walther: the telegraph wire on the Trans-Caspian railway had to be renewed after eleven years, as it had lost half its diameter by the action of blown sand, and on one occasion the sand-blast was sufficiently powerful to scrub all the paint off the locomotives on the same line of railway.

It has been shown in the foregoing chapters that the general effect of denudation of all kinds is to lower the surface of the land and eventually to smooth out differences of elevation, though in the intermediate stages the relief may be highly accentuated. The theoretical limiting surface thus assumed to be produced as the ultimate result of denudation is called a *peneplain* or *peneplane*. There has been a good deal of unnecessary discussion as to spelling of this word: the meaning, 'almost a plain,' is obvious. It may be doubted whether peneplanation has ever been carried to the limit: something has probably always occurred to interrupt the process. Most of the land-surfaces discovered among the older rocks are by no means flat. At the present time most of the world's greatest plains are due to deposition rather than to denudation. As will be shown later a plain of marine denudation is also a possibility and would be difficult to distinguish from a subaerial peneplain among the older rocks.

CHAPTER V

TERRESTRIAL DEPOSITS

Climatic Zones.—In the first chapter of this book it was stated that the land surfaces of the world can be divided into four climatic zones. This now requires a little amplification, since it happens that both the arctic and the temperate zones as there defined each show a considerable amount of variation. In the following list the last two items are the same as those previously given, but each of the others is divided [1]—

1. Glacial.
2. Tundra.
3. Steppe and Prairie.
4. Temperate forest.
5. Subtropical desert.
6. Tropical forest or jungle.

It is not necessary that all of these should be present, and it has already been remarked that in parts of Central Asia the true temperate zone is absent. In other areas either steppe or tundra, or even both may be absent: temperate forest often merges gradually into tundra and in most cases steppe is best regarded as alternative to forest: for example, the Russian steppes join the desert belt and are far south of the Scandinavian and north Russian forests.

However, it will be more convenient to discuss terrestrial deposits from a different point of view, not geographically, but according to origin, as the result of the working of the different geological agents whose modes of action have been described under the general heading of Denudation. As we have seen, the final resting-place of denuded material is the ocean-basins, where it is deposited to form the sedimentary rocks; but much of this material is not carried directly to the sea as soon as it is broken up by agents of weathering and denudation. Some of it finds a temporary resting-place in lakes, while some remains, for a time at any rate, on the surface of the land. It is with this last that we have here to deal.

The Regolith.—The character of such terrestrial accumulations naturally varies according to the physical conditions under which they were formed and the materials of which they are composed. A good deal of attention has been paid to this subject in America, and the following classification was proposed by Merrill.[2] In this scheme no

[1] This scheme was originally worked out by Nehring in the *Geological Magazine* for 1883. For an excellent discussion of the whole subject see the late Professor Marr's *Deposition of the Sedimentary Rocks*, Cambridge University Press, 1929, Chapter V.

[2] *Rocks, Rock-weathering and Soils*, 1897, p. 300.

mention is made of soils in the ordinary sense of the word, since the soil is merely the superficial layer highly modified by the growth of vegetation. For the sum-total of all these terrestrial accumulations Merrill proposes the convenient term *Regolith.*

Merrill's Classification of the Regolith.

Sedentary	Residual	Residual gravels, sands and clays, wacké, laterite, terra rossa, etc.
	Cumulose	Peat and swamp deposits (in part).
Transported	Colluvial	Talus and cliff débris.
	Alluvial	Modern alluvium and swamp deposits, loess (in part).
	Aeolian	Wind-blown sand, loess (in part).
	Glacial	Moraines, drumlins, eskers, etc.

The wording of this classification has been slightly modified by the omission of a few terms understood only in America. The terms in the second column mostly explain themselves; the only new words here are *cumulose,* which refers chiefly to accumulations of vegetable matter in situ, i.e. growth in place, and *colluvial* (derived from *colluvies,* a mixture), which signifies heterogeneous aggregates of rock débris derived from various sources, such as screes and mud-flows.

It will be seen that some of the items in this list have already been described to some extent in the chapters on weathering and earth sculpture. Again, many or most of these types are found in a more or less altered state among the older sedimentary rocks, to be dealt with in Chapter IX. Here, therefore, for the sake of completeness there must necessarily be some repetition of what has gone before and anticipation of what is to come. For this reason not much will be said in this chapter on the actual mineral and chemical constitution of the deposits described. Attention will be confined as far as possible to origin and geological significance rather than to petrographical character, and some terms will be used by anticipation, without the strict definitions given in later chapters.

Residual Deposits.—Under this heading are included various deposits now covering the earth's surface in places, and consisting of material left behind during the ordinary processes of subaerial denudation. The mode of formation of residual deposits is fairly obvious, and scarcely needs detailed description. When a rock consisting of heterogeneous materials is weathered, some of its constituents are removed more easily than others; for example, nearly all soluble rocks, as limestone, contain more or less insoluble residue. In the case of a sandstone with calcareous cement, the latter is easily dissolved by water, and an aggregate of loose sand-grains left behind. The finer constituents of conglomerate may be washed away, leaving the pebbles behind, and so on. Thus are formed accumulations of clay, sand,

gravel, etc., which are to be regarded as the residues of the rocks of which they once formed part. In the same way some of the constituents of igneous rocks are more easily removed than others, which are left behind, and often undergo marked chemical and physical changes. Evidently deposits of this kind show a close affinity to ordinary soils, from which they differ in many cases only by their greater thickness. In recently glaciated regions such residual deposits do not generally show a great development, as sufficient time has not elapsed since the removal of all loose material by ice; and the formation of the heterogeneous accumulation of varying origin known as glacial drift is not residual, since it involved much transport. Residual deposits are best developed in regions covered by luxuriant vegetation, which prevents removal of weathered material. Consequently, in tropical regions the rock is often completely hidden by a great thickness of material of this kind, which is essentially soil above, graduating downwards into rotten rock, or sometimes quite sharply separated from fresh rock.

As an example of residue from a limestone, mention may be made of the deposit known as *Terra Rossa*, a red ferruginous material which covers large areas on the limestones of the Adriatic region, and on the plateau of Franconia and Suabia. It is simply the insoluble residue of the limestone. With this may be compared the reddish soils often found on the Carboniferous Limestone of the north of England and some of the Jurassic Limestones of the Midlands. The widely spread deposit known as Clay-with-flints in the south of England was formerly believed to be simply the insoluble residue from the Chalk, but it is now thought that some of the Tertiary clays have taken part in its formation. North of the Thames some of the Clay-with-flints appears to be simply boulder clay of direct glacial origin. On some of the higher elevations of Cambridgeshire and Norfolk there are to be seen thick accumulations of gravel, chiefly flints, but containing also boulders of foreign rocks. These plateau gravels are believed to represent the heavy residue of the boulder-clay, from which the finer material has been removed by water action. At the foot of the South Downs, and especially in the neighbourhood of Brighton, there occurs a peculiar deposit known as the Elephant-bed, or more commonly as the Coombe Rock. It is a mass of angular flints and Chalk, which show little signs of rolling by water action, and is entirely unstratified; the only organic remains are broken teeth of elephant and horse. For a long time the Coombe Rock was supposed to be a marine deposit formed by a temporary submergence, but all the evidence is against this view; and it is in all probability an accumulation of material carried down from the higher parts of the Chalk downs at a time when the soil and subsoil was frozen to a considerable depth, so that rain was unable at once to sink in to the Chalk as it does now, but formed rapid streams

on a steeply inclined surface. The Coombe Rock is thus to be regarded as a torrential deposit formed during the prevalence of glacial conditions over Britain, but in a region not invaded by the ice-sheet. A somewhat similar accumulation, known as *Head*, is found in other parts of the south of England beyond the limits of glaciation, especially in Cornwall.

Another important class of residual deposits consists of those formed by alteration in place of igneous rocks. The outcrop of a granite is often covered by a layer of coarse sandy or fine gravelly material, according to the grain size of the original rock, and consisting of quartz alone or of quartz, felspar and mica, according to the degree of chemical decomposition of the minerals, quartz being much more stable than the others. Igneous rocks without quartz often weather to a clay-like substance, sometimes called *wacké*. The composition of this is complicated and uncertain: it consists mainly of the group of aluminous silicates and hydrates which for the present may be called clay-material.

In many tropical regions there are very extensive developments of a group of deposits mainly though not entirely derived from igneous rocks, the most conspicuous being laterite and its variety bauxite. Similar deposits are also found here and there among the older rock-formations, e.g. in France and Ireland, where bauxite is worked as the chief ore of aluminium. There is also in India a manganiferous variety. During the last forty years there has been much controversy as to both the composition and the origin of these rocks, and even now the questions are far from settled. It should first be mentioned that some of the red material so commonly used for road-surfacing in tropical lands under the name of laterite is not really such at all, but simply iron-ore of various ages. True laterite is a red, yellowish or dark brown material with a curious cellular or vesicular structure, often so strongly marked that in earlier days some of the darker varieties were mistaken for lava. One notable property is that underground it is often quite soft, and can be cut into blocks with a spade: it hardens rapidly on exposure to air and forms a good building material; hence the name (*later* = a brick).

It was formerly stated that laterite and bauxite consist essentially of hydroxides of iron and alumina, all silica having been washed out in weathering, but it is now known that combined silica is present in considerable quantity in most types and that the aluminous varieties show a close approach to kaolinite in composition: only in varieties of laterite derived from basic rocks with low silica are the hydroxides dominant. As to the exact mode of origin of laterite and bauxite it is impossible to say anything definite at present. All the older theories are open to strong objections of one sort and another and the whole subject is in a very unsatisfactory position.

Cumulose Deposits.—These for the most part consist of material which has actually grown where it is now found. Consequently, they

are chiefly of vegetable origin. By far the most important of them is the material comprised under the general designation of *peat*, which is described on p. 180. Probably also mangrove swamps and many other tropical vegetable accumulations come in here, although there is not much information on the subject. Their usual representative among the older rocks is of course coal in all its varieties. Much coal was undoubtedly formed in deltas.

Colluvial Deposits.—This heading includes chiefly the piles of débris found at the foot of precipices and steep slopes generally, and commonly known in this country by the name of *scree.* We must also include here the material brought down by landslips, and the peculiar phenomena best described as *mud-flows.* It is unnecessary to enter into details of the formation of scree deposits : the subject has already been dealt with under the heading of Denudation. Screes are found in all mountain regions, and are specially well seen in the English Lake District. Mention may be made of the great Wastwater screes, and those on the west face of Skiddaw. The angle of inclination of a scree naturally depends on the nature of the material, but it rarely exceeds 30°. It is impossible to distinguish sharply between scree and landslips, which are connected by innumerable gradations : the formation of landslips has already been described in some detail. Scree formation is also very conspicuous in mountain regions with an arid climate : examples of deposits of this origin are abundant also among the older rock-formations and when cemented into a solid form are known as *breccias.* They are characterised by the angular form of the component fragments, as distinguished from the rounded pebbles in conglomerates.

Alluvial Deposits.—Under this very wide heading are comprised all the deposits formed by streams and rivers as a result of transport and deposition. We cannot logically exclude even the masses of great stones and coarse gravel formed in the beds of mountain torrents, but the most important are the finer-grained deposits of the flood-plains and deltas of rivers, and the fillings of lakes. Estuarine deposits containing marine elements are to be excluded. It is to be emphasised that from this point of view there is a great difference between upland and lowland rivers : between the clear, rapid, rocky burns and becks of the north and the slow, muddy, reed-choked, canal-like watercourses of the plains, but of course all intermediate forms exist, even in the system of a single river. Here again at the risk of tiresome repetition, stress must be laid on the importance of floods, either seasonal or at irregular intervals. It is in the flooded state that rivers do nearly all their work, both of erosion and of deposition. This is clear even in British rivers : many South African rivers are normally wide expanses of stones and gravel, with hardly any water, though all the material is obviously water-borne and water-worn, and it is well known that Australian rivers often dry up altogether, except perhaps for a few pools.

The coarser elements of river-deposits are characteristically rounded and smoothed and as on beaches so in rivers, there is naturally much sorting of the material: coarse in the rapid parts, finer where the current is slow, grading to sand, silt or even mud in quiet pools and on flood-plains and in deltas. The types of material found in alluvial deposits naturally show much variation in size: for practical purposes the following terms are useful and mostly explain themselves: boulders, cobbles, gravel, sand, silt, mud. Many attempts at a classification graded according to scales of size have been made by petrographers, mining engineers, workers in soil-science and others, but for our present purpose this is hardly necessary; the matter may well be left to common sense. There are objections to the word boulder, as it might be taken to imply a glacial origin (from boulder-clay), but there is no satisfactory substitute. For blocks of such a size as could be used for street-paving the name cobble has been suggested and has some advantages, but it excludes the larger sizes. It also seems quite hopeless to fix an upper limit of size for gravel or shingle, and fine gravel grades down into coarse sand. Most alluvial deposits contain more or less vegetable matter and some of them grade into the cumulose class: e.g. fen-peat, described in Chapter IX. They generally yield a very rich soil and form some of the most fertile districts of the world.

Some of the best examples of alluvial flats in this country are found alongside of meandering rivers, often occupying the concave sides of the big bends. For this kind of thing many local names are in use. In Yorkshire alone, for example, they are known in different parts of the county as *carrs*, *ings* and *holms*, and no doubt other names could be found. In Somerset a *moor* (e.g. Sedgemoor) is an alluvial plain and not high ground as in the north. The Fenland of eastern England is a rather exceptional case, as in parts of it there is much marine silt: it belongs partly to the estuarine class, although now many rivers wander over it, and form alluvium during floods—or any rate they did so into historic times, before there was any drainage. Occasionally they do so even now, when floods get out of control, as in 1928 and 1937.

When a river runs in at the head of a lake it begins to drop its load of sediment in the still water: a delta forms and extends, often assisted by the growth of water plants, until eventually the whole lake may be filled up. The later stages of the filling often include a good deal of peat, especially at high elevations, as in many of the old tarns of the Lake District. In some instances also deltas are formed by streams entering at the sides of the lake and growing outwards. Derwentwater and Bassenthwaite in Cumberland once formed a single lake about 9 miles long: two considerable streams happened to enter it from either side rather above the middle and their deltas eventually met. It is now cut into two lakes separated by an alluvial flat some 3 miles

long, over which the river meanders (Plate XII, (ii)). Buttermere and Crummock Water were also once continuous, but are now separated by the delta of a side stream, which has driven the main river over to the S.W. side.

Deltas.—Delta formation in its simplest form is best seen in big freshwater lakes, owing to absence of interference by tides and currents, but of course the deltas formed where great rivers run into the sea are of far more importance. It is hardly necessary to explain that the name arises from the resemblance in shape of the delta of the Nile to the Greek capital letter of that name. In the case of an ideal delta, if the slope of the floor is moderate the following types of deposit can be distinguished: the chief materials carried by the river being sand, silt or mud, according to the velocity of the current. First of all we shall probably find a series of fine-grained material spread out in beds flat on the original floor of the sea, forming the *bottomset* beds: suppose now a flood or series of floods occurs, then coarser material will be spread over these, often very much like the building of a railway embankment or slag-dump by tipping trucks of material over the end. The result is the formation of a series of *foreset* beds each consisting of coarse material, often separated by finer layers, the whole with a steep apparent dip, which is wholly deceptive as to the real thickness of the deposit. On the upper surface of this series there may again be laid down more flat-lying strata, the *topset* beds. Often after a slight tilting of the area the whole process may be repeated and sometimes there are complications due to slumping of masses of material from the steep seaward end. Some deltas, however, consist mainly of flat-lying bottomset and topset beds, with little or no foresetting, although even in these the bedding on a small scale is often very irregular, and endless variations are possible. A very notable feature of large deltas is that the river after a time tends to split up into branches, which wander over its surface, somewhat like the meanders in the higher parts of its valley, with frequent changes of course. Since delta deposits naturally remain soft and unconsolidated for a long time, this may result, especially during floods, in what are conveniently known as *wash-outs*, where a channel scooped out of the older alluvium may be filled in by material of later date and different character. Many examples of these are known also among the older rocks; for example, in England, among the Coal-measures and the Middle Jurassics of Yorkshire.

It is hardly necessary to enter into a detailed description of the deltas of the Nile and the Mississippi and the great plain of China, which are the classical examples given in all books on geography: it will only be added that the Mississippi delta consists very largely of fine mud, while the deposits of the Nile delta contain, in addition to silt and mud, a good deal of sand blown into the river from the Libyan desert.

Aeolian Deposits.—Wind as an agent of denudation has already been considered in Chapter I, but it is necessary here to give some account of the character of the deposits in whose formation wind plays the chief part. Aeolian deposits are most largely developed in those arid regions popularly known as deserts, but they also play an important rôle in some temperate regions, as sand-dunes, steppe-deposits and loess: they form a peculiar and characteristic type of sedimentation which is largely developed both at the present day and in the older formations.

The special character of the dry weathering of desert regions has already been described, and it was pointed out that the disintegration of the rocks is almost entirely due to the effects of strong solutions and high temperatures. These lead to a rapid and deep breaking up of the rocks, and provide vast quantities of dry, finely divided material to be acted on by agents of transport. Besides gravity, the only transporting agent of any importance is wind: water action is rare and local.

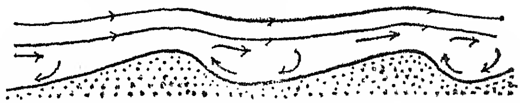


FIG. 46.—DIAGRAM TO SHOW THE FORMATION OF SAND-DUNES. The direction of the air-currents is shown by the barbed lines. (After Vaughan Cornish.)

A great part of the Sahara and other extensive deserts consists of a vast sea of sand of a grey or yellow colour, often mixed with gypsum. The surface is by no means level, but is broken up into great sand-dunes from 50 to 400 feet high, like petrified waves; sometimes between these the rocky floor is exposed. These dunes appear to be a permanent feature of the landscape: when once formed they remain fixed in the same position and do not possess a movement of translation, like the sand-hills of more northerly regions. Wind action is very powerful, and during a sand-storm, or *Samum*, there is great transfer of material from one dune to another, but their positions as a whole remain the same. The reason for this is that their place is determined once for all by some irregularity of the surface, and it is only under exceptional circumstances that changes are produced. Sometimes, however, a chance obstacle, even a dead camel, is sufficient to cause an accumulation of sand during a storm, giving rise to a new dune. All the groups of dunes along the caravan routes possess names, and are well known to the natives as permanent features.

Individual dunes show a gentle slope on the windward side, and a steep slope to leeward, due to eddies in the air-currents, which have a sort of scooping action behind their crest (Fig. 46). The steep slopes on the leeward side form a great hindrance to travel, and caravans often have to travel along the foot for a great distance before a chance

depression allows them to cross over into the next valley. As a rule the distance from crest to crest of the waves varies from half a mile to a mile in the open desert.

Form and Arrangement of Sand-dunes.—Since the piling up of sand into dunes is wholly due to the action of the wind, their form and arrangement is controlled by the direction and intensity of the prevailing winds of the district. When the sand is merely heaped up into mounds, these are often arranged in rows either parallel to the wind or at right angles to it. When it takes the form of long narrow ridges, true dunes, the arrangement of these follows the same law; the parallel or transverse character of the ridges depends on the relation between the supply of sand and the average strength of the wind. In North-western India the prevailing winds are from the S.W., and the supply of sand comes from the same direction. Near the coast the ridges are parallel to the direction of the wind, while in the interior they are transverse to it, and this seems to depend on diminishing strength of wind at a distance from the coast. In the deserts of Central Asia the sand is often piled up into peculiar crescent-shaped forms with their convex sides facing the wind. These are called barchanes and are very characteristic. In regions where the wind is variable in direction this regularity of arrangement is naturally destroyed, and the sand is merely piled up into confused heaps of no definite form and arrangement; and similarly the ideal symmetry of a dune with its steep leeward and gentle windward slopes is also obliterated by changes of wind. These large-scale dunes are characteristically covered by innumerable ripples in the sand, which of course are small scale sand-waves, like the small ripples on big water-waves at sea.

Sand-dunes and Sand-hills.—In many temperate regions there are to be found along the coasts great accumulations of blown sand. These are of essentially the same character as the sand-dunes of the desert, but they differ in this respect, that the sand is mostly prepared by marine erosion, and not by dry weathering. Consequently, sand-hills are most conspicuous along coasts exposed to the prevailing winds of the region. In Europe, therefore, accumulations of blown sand are most noteworthy on coasts much exposed to westerly and south-westerly winds, such as Devonshire, Wales and Cumberland, some parts of the west of Scotland, and the French coast of the Bay of Biscay. They are also found to a less extent on the eastern coasts of Scotland and England, where easterly winds are prevalent. The mode of formation of these accumulations is very simple: the sand is prepared on and near the beach by wave-action, cast up by the waves and carried inland by the wind; and the formation of the sand-dunes follows much the same laws as in desert regions, except that they are not stationary, but in a continual state of movement, often rapid, so that new tracts of country are continually being overwhelmed by them.

A very interesting example of this is the historic case of the Culbin Sands on the shores of the Moray Firth in Scotland, where, in the seventeenth century, several thousand acres of fertile land are said to have been overwhelmed by sand-hills during a single storm.

The Loess.—The origin of the peculiar deposit known as *loess* has given rise to much controversy: it appears, however, that no single explanation will account for all the materials known by that name. The classical description is that given many years ago by von Richthofen of its occurrence in North China. He seems, however, to have exaggerated the thickness, not having realised that in many instances the loess is merely plastered up against the sides of steep hills of solid rock, and does not actually form the hills. At any rate it is clear that the typical loess of Asia and Eastern Europe is an aeolian deposit formed under an arid climate: it is also clear that in Europe loess formation has taken place more than once and that it was somehow associated with glaciation. It is now generally believed that the loess was formed in the non-glaciated areas contemporaneously with the widest extension of the ice-sheets, as it was only then that the climate was dry enough for wind-transport to be of importance, the interglacial periods being much more humid. In many places it has been shown that the older loess was weathered and decalcified before the deposition of the newer: this weathering must have taken place during the intervening humid period.[1]

The typical loess of Europe and Asia and of a very large area in the Mississippi basin is a fine-grained calcareous loamy material of a yellowish or brownish colour and penetrated by innumerable fine vertical tubes due to the rootlets of grass growing on the surface during its formation. This indicates steppe conditions. Owing to these tubes, when eroded it can stand up as very steep or even vertical faces, a characteristic of the scenery of loess regions.

It is doubtful whether much of the material called loess in Western Europe, e.g. in Belgium, is really the same thing: it shows a strong likeness to the brickearths of South-eastern England, whose origin is doubtful. It will be necessary to refer to the loess again in later chapters, as it undoubtedly has an important bearing on the difficult problems of the Pleistocene glaciation of Northern Europe.

Steppe Deposits.—Only a brief reference need be made here to the type of deposit prevailing over very large areas in Southern Russia and Western Asia, which obviously has much in common with the loess. The typical Steppe consists of wide sandy plains more or less grass-covered, with a distinctly arid climate. As a rule the soils contain very little vegetable matter: when this is more abundant, owing to a somewhat wetter climate, the result is the famous Black Earth, or Tchernozom, a soil of quite remarkable fertility. Many of the prairie

[1] Woldstedt, *Das Eiszeitalter*. Stuttgart, 1929, pp. 111–124.

soils of North America and similar ones in Argentina are closely allied. All this, however, is soil-science rather than geology.

The Tundra Region.—Of somewhat greater geological significance are the deposits now existing in the tundra region. This comprises all those parts of Northern Europe and Asia and North America which though not under a permanent ice-cap like Greenland, are still some of the coldest regions of the earth. The dominant deposits, especially the vast development of peat, really belong to the cumulose group, but owing to the very low temperatures it may be said that glaciation also plays a part, and the subject may conveniently be mentioned here. The most notable feature is that throughout the true tundra region the subsoil is frozen to a great depth for a great part of the year, and over very large areas even all the year round. It is somewhat surprising to find that in Central Siberia this last-named condition prevails even as far south as the latitude of London.

To put the matter as shortly as possible, the chief result is the development of peaty deposits on a very large scale, owing to the extremely slow decomposition of vegetable matter, largely mosses, under such conditions. Here also as already briefly mentioned extraordinary effects are often produced by spring floods in great rivers flowing from more southern latitudes to the Arctic Sea over the still frozen ground. In Siberia many rivers and shallow lakes apparently freeze solid to the very bottom in winter, and in places the frozen soil-belt is known to extend downwards for several hundred feet. Every one has heard of the mammoths and other animals preserved in natural cold storage in Siberian gravels for thousands of years. Many of these frozen gravels contain a good deal of gold, which can be mined with profit even in such conditions, and they have therefore been very fully investigated.

The glacial deposits of Merrill's classification are dealt with in the next chapter.

CHAPTER VI

SNOW AND ICE AS GEOLOGICAL AGENTS

Formation of Snow and Ice.—In earlier chapters we have studied in detail the geological activity of water in the liquid state: it is now necessary to consider in a similar manner its effects when in the solid form, as snow and ice. Under the ordinary atmospheric pressure the transition of pure water from the liquid to the solid state occurs when the temperature of the water is 0° on the centigrade scale. In many parts of the world the temperature of the air frequently falls below this limit, and as a consequence water is solidified. The surface water of the land, in rivers and lakes, freezes to ice, and sometimes the sea also, although the freezing-point of salt water is much lower than that of fresh. Again, the aqueous vapour of the atmosphere, when condensed at a temperature below freezing-point, falls as snow or hail.

The occurrence of low temperatures under natural conditions depends upon several factors, of which the chief are latitude and elevation above sea-level. It is well known to every one that the climate becomes progressively colder from the equator towards the poles, and also as we ascend above sea-level; and it is unnecessary to discuss the cosmical and meteorological causes of these phenomena. Geology is concerned solely with the results, which are of extreme importance.

To study in full completeness the geological effects of low temperatures we must turn to the polar regions, where they occur on the largest scale. However, many of the fundamental facts have been ascertained from an examination of the phenomena displayed in mountain regions in lower latitudes, and in particular the Alps.

Cause of Glacial Conditions.—It is well known that in all parts of the world, at a certain variable height above sea-level, the mean annual temperature of the year is at or below freezing-point, and this condition favours the accumulation of ice and snow; but this is not the sole, or even perhaps the principal, determining factor. The necessary condition for the existence of perpetual ice and snow is that the amount formed during the cold season shall be equal to or greater than the amount removed by melting during the warmer period. Given a sufficiently low temperature, the lower limit of the snow is obviously the level at which there is equilibrium between the snowfall of winter and the melting of summer; above this line there must be accumulation of snow, unless this is compensated for by an actual transfer of material from a higher to a lower level, and this compensation is as a rule effected

by the movement of glaciers, which often extend, as rivers of ice, far below the normal snow-line. This is possible because material is carried down faster than it can be removed by melting. It follows from this that the lower limit of an ice-stream is rarely stationary for any length of time. It is generally either advancing or retreating. If the supply from above is checked while melting is still going on below at the same rate, the front of the ice will retreat, although the stream may actually be moving downwards.

It is evident, therefore, that one of the necessary conditions for the existence of perpetual ice and snow, apart from temperature, is a sufficiently large precipitation. The coldest region of the globe appears to be Eastern Siberia; but here the surface of the ground is not permanently snow-covered, because the snowfall of winter is comparatively small, and the heat of summer is sufficient to melt it. In Greenland, however, there is an enormous accumulation of ice and snow, because this region is well within the reach of the moisture-laden winds from the Atlantic, and the snowfall is large. In the Antarctic also similar conditions exist on an even larger scale.

Snow-fields and Glaciers.—In regions of heavy precipitation, above the snow-line snow accumulates to a great depth, especially on plateaus and in the valleys. The pressure of the overlying layers consolidates the under parts into a firm, more or less coherent, mass. This kind of ice derived from snow is called in the Alps *névé* or *Firn*, and these terms are now in general use in other districts. As this *névé* accumulates it begins to move downwards, and forms what are commonly spoken of as glaciers. Although ice, regarded in small masses, is a very brittle solid, yet in bulk it possesses some of the properties of a viscous fluid, since it is able to flow; and in many ways the behaviour of glaciers presents certain analogies to that of rivers, and they may be conveniently regarded as rivers of ice. There has been much controversy as to the mechanics of the movement of glaciers, and the question is still far from settled. The subject will be dealt with in a later section (see p. 107), after some actual examples have been described. Ice formed from snow by pressure possesses some peculiar characters, serving at once to distinguish it from ice formed directly by the freezing of water on the surface of lakes, rivers, or the sea. In a few cases, again, considerable masses of ice are formed by the freezing of the lower layers of masses of water in contact with a cold floor. This *ground-ice* is only of importance in arctic or sub-arctic regions, where, however, it often occurs on a considerable scale.

Avalanches.—Where snow accumulates to a great depth in mountain regions, where steep slopes are common, it often falls in large masses by its own weight. Such snowfalls are known in the Alps as *avalanches* or *Lawinen*. They have been exhaustively studied by Heim and others, and several types have been distinguished. Primarily they

may be divided into ice-avalanches and snow-avalanches, and the latter alone are of much importance. It is often assumed that avalanches are of exceptional occurrence, and necessarily very destructive, but this is by no means the case. Avalanches are a perfectly normal and regularly occurring phenomenon over the whole region of the Alps, and they also occur in all other snow-clad mountain-ranges. In many localities an avalanche is a regular yearly occurrence, which takes place at a more or less definite time, and in some cases it has been observed that the avalanches from the different parts of a given mountain mass fall yearly in a fixed order. Like glaciers, avalanches have their own gathering-ground, their well-defined track, and their place of melting. They often bring down considerable quantities of rock-material, and their path is often scratched and more or less polished. When left behind on the melting of the snow, this rocky material looks much like the deposits of glaciers.

In the Alps avalanches most commonly originate at a height somewhere between 6,000 and 8,000 feet, where the yearly snowfall usually amounts to about five metres. There are two types of snow-avalanches, which are called in Switzerland *Staublawinen* and *Grundlawinen.*

Staublawinen occur in the coldest weather in winter, and consist of dry, powdery, newly fallen snow, which will not cohere, and often slips bodily off an inclined surface of older snow. The dry snow rises in the air like a cloud as it falls, and causes a strong wind-blast to arise, following the course of the snow. This wind often does more damage to the buildings and trees in the valleys below than the snow itself, since it travels further.

Grundlawinen occur in spring, during thaw-weather, especially after a sudden rise of temperature. At this time the snow is wet, heavy and adhesive, and melts from below; this produces hollows, and often causes it to slip off steep surfaces. The movement is a complex mixture of flowing, rolling, sliding and falling, and when it stops the whole mass is almost instantly solidified by regelation. The wind action here is inconspicuous.

When the snow is in a condition of nicely balanced equilibrium an avalanche is often started by some very trifling disturbance, such as an incautious footstep.

Glaciers.—In most cases, however, the removal of snow from a higher to a lower level is not the sudden process outlined in the last paragraph, but of a much slower nature. As before pointed out, the snow is consolidated into ice, and moves downwards in this form, in a gradual manner, producing ice-streams or glaciers. Glaciers in the ordinary sense are found in most high mountain regions, even in tropical latitudes where the elevation is great enough. Their scientific study originated in the Alps, and has now been extended to many other parts of the world. The terminology employed in describing the

various features of glaciers is mostly, therefore, of Swiss origin, being derived from the local dialects of the Alpine region.

Glaciers of the Alps.—In the higher parts of the Alps glaciers are very abundant, although none of them reach the great dimensions of those of some other regions. In all there have been enumerated some 1,200 permanent and independent masses of ice, but only about 250 of these are glaciers of the first order. A large proportion of the remainder are mere accumulations of snow in hollows, which scarcely merit the name. It is obviously impossible to draw any definite distinction between a true glacier and a snow-field, since one merges into the other, and the upper part of a true glacier is always a snow-field.

A large glacier may usually be divided more or less definitely into two regions—an upper one composed of *névé* or *Firn*, and a lower one of ice; the limit between the two, where the snow changes to ice, is often spoken of as the *Firn-line*, but this of course applies to the surface only, since the lower layers above this line are consolidated by pressure. It is to be noted that this *Firn-line* does not necessarily coincide with the snow-line on the rocky parts of the adjoining mountains; for example, in the Finsteraar district the *Firn-line* is some 650 feet lower than the snow-line. This difference is due to the movement of the glacier. The mass of ice below this *Firn-line* is commonly regarded as the true glacier. It appears, therefore, that in the *Firn* region precipitation is in excess, and below it, melting. The *Firn-line* represents the condition of equilibrium between the two.

The upper part of a glacier-basin, then, is filled with coarsely granular ice, the *Firn* or *névé*. These *névé*-fields are not generally simple, except in the case of the smaller glaciers, but they usually comprise several tributary valleys, as in the case of the well-known Aletsch glacier, and most of the other large glaciers of the Alps. The Mer de Glace consists of three main streams, each of which is again made up of tributary branches. The glaciers of the Alps very rarely branch downwards, though this is common in high northern latitudes. Owing to the configuration of the ground in the Alps, i.e. sharp peaks and ridges, without high plateaus of large extent, several glaciers never radiate from a common snow-field, as they do in Norway, Spitsbergen and elsewhere. Hence simple, independent glaciers of this kind are distinguished as the *Alpine* type.

Characters of Alpine Glaciers.—Turning now to a consideration of the ice-stream, the glacier proper, we find that its surface is not smooth, but is diversified by various features. The glacier rests on an uneven floor, and this unevenness is the cause of inequalities at the surface. Sometimes the glacier falls over a steep slope, forming an ice-fall, analogous to a rapid or a water-fall. This causes tension, and results in the formation of transverse cracks of varying width, called *crevasses*, which are often of great depth (Plate XIII (i)). Again, since the ice

behaves more or less like a viscous fluid, it obeys the ordinary laws regulating the flow of streams, and the centre flows more quickly than the sides; this results in the formation of crevasses, starting from near the sides and pointing up-stream (see Fig. 47). Sometimes also longitudinal crevasses are formed, and the diagonal crevasses may be regarded as the resultants of combined transverse and longitudinal strains. Since the superficial parts of a stream flow more rapidly than the under parts, there must also be differential movement between different layers in the ice, resulting in shearing strains, which often set up foliation in the ice. When a glacier passes over a sudden change of slope in the rock floor, as for example on issuing from a hanging valley, such complicated strains are set up, that the ice is broken up into a bewildering mass of blocks and pinnacles, exceedingly difficult to traverse. A good example may be seen at the top of the ice-fall of the Rhone glacier, when it descends into the valley above Gletsch, near the Furka Pass. Such masses of ice-blocks and pinnacles are called *séracs*.

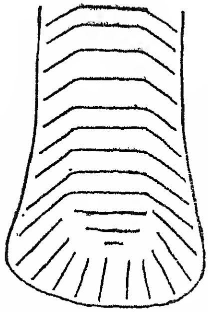


FIG. 47.—CREVASSES IN THE RHONE GLACIER.

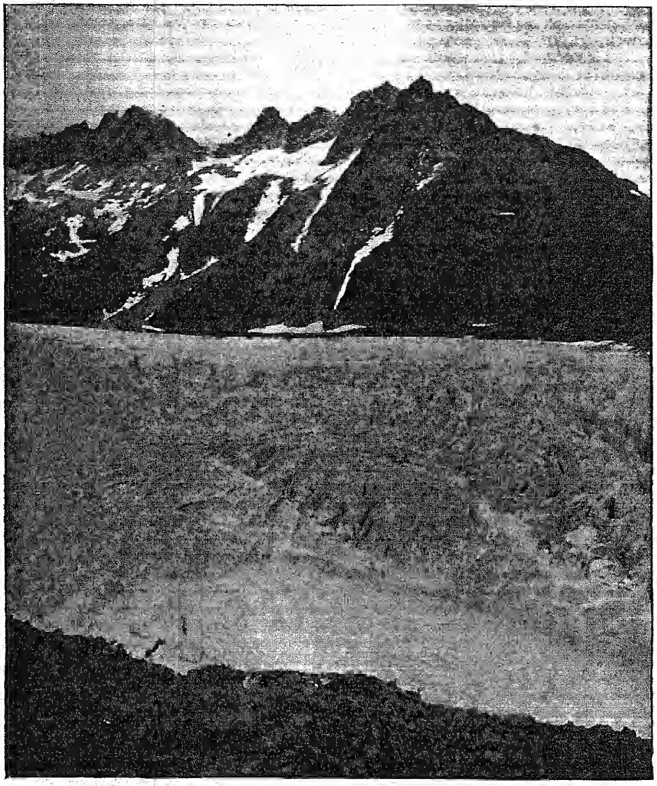
In the middle, transverse; near the edges, directed downwards and outwards.

In a few cases ice-falls are developed to such an extent in the course of a glacier that there is an actual discontinuity; that is to say, the ice-stream falls bodily over a cliff and collects in a pile at the bottom. Owing to melting and refreezing, this mass of ice cements itself again into a solid stream and continues on its way: such are spoken of as *regenerated glaciers*.

Moraines.—Glaciers of the Alpine type, surrounded by considerable areas of bare rock constantly undergoing denudation, collect in their course a good deal of rock waste, which at first at any rate is carried on the surface of the ice, and forms what is called in the Alps *moraine*. There is a good deal of confusion as to the use of this term in geological literature, as it is applied indiscriminately both to the rock waste carried on the surface and to the piles of rubbish deposited at the melting end of the glacier, much of which is derived from the floor and sides of the valley, below the level of the ice.

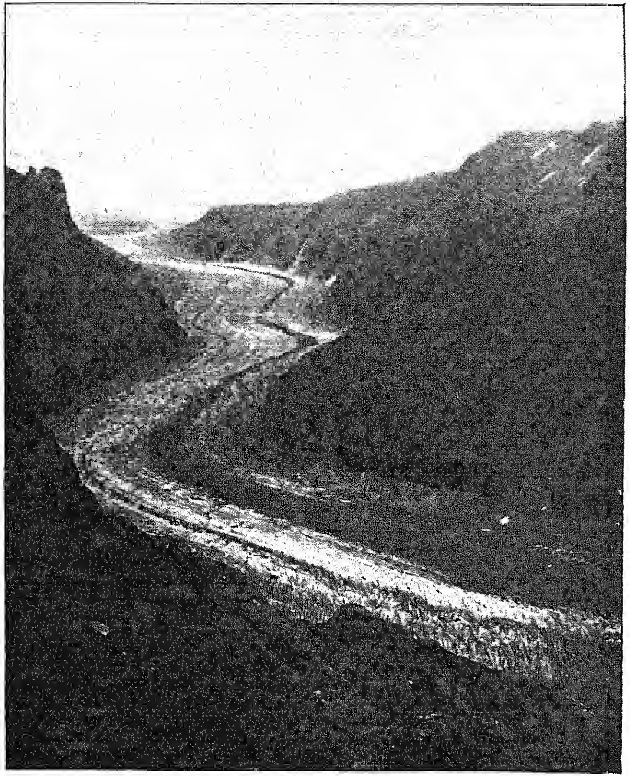
Most of this rock waste from the surrounding peaks naturally falls at or near the side of the glacier, and is carried on as a marginal stream: this is called *lateral moraine*. When two glaciers coalesce, the two lateral moraines on the inner sides unite and form a central or *medial moraine*. In highly complex glaciers, such as the Aletsch, numerous medial moraines can be distinguished following the windings of the stream, and each formed by the union of two tributary glaciers. (See XIII (ii)). Some large glaciers carry so much surface moraine

PLATE XIII



J. J. Lister, photo.

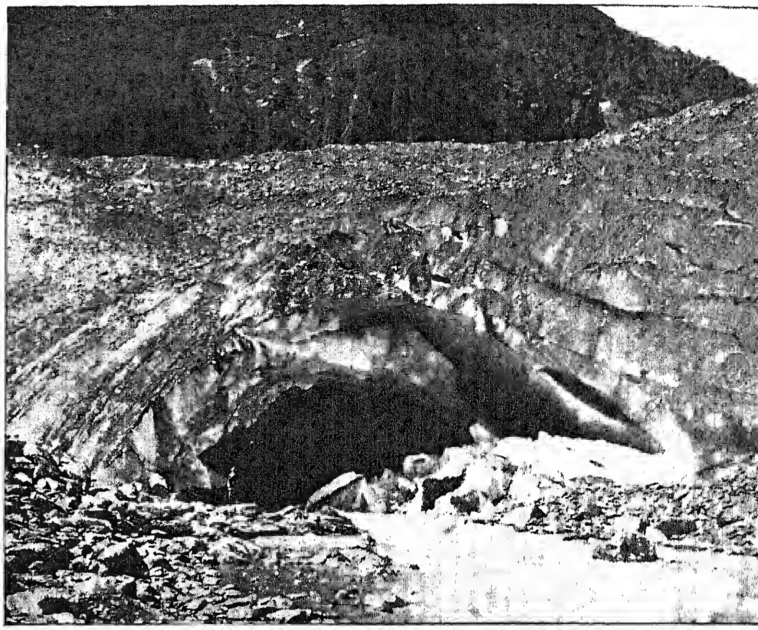
(I) CREVASSES IN THE RHONE GLACIER APPROACHING THE ICE-FALL.



J. J. Lister, photo.

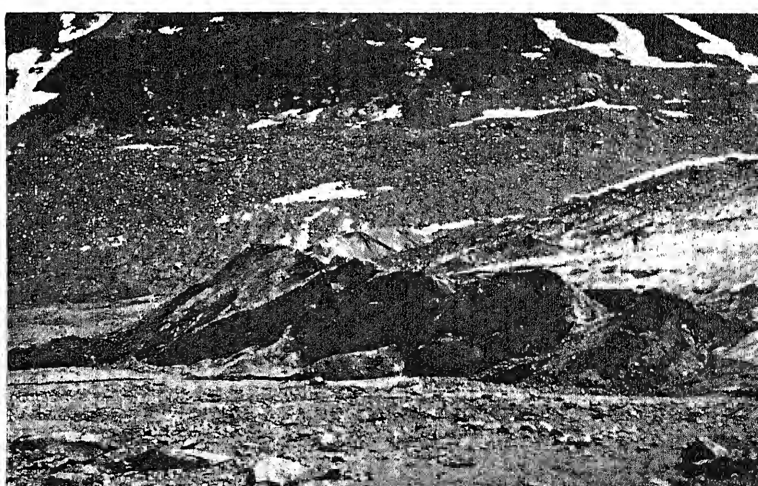
(II) FIESCHER GLACIER FROM THE PATH TO THE MÄRJELEN SEE.

PLATE XIV



J. J. Lister, photo

(I) ICE CAVE AT END OF FEE GLACIER, SWITZERLAND.



J. J. Lister, photo

(II) CRESCENTIC TERMINAL MOUND OF THE OBERAAR GLACIER.

formed in this way, that the ice may be completely hidden: this is the case with the lowest three miles of the Unteraar Glacier, which merely looks like a great plain of dirty gravel.

As the moraine material travels onwards, part of it is frequently swallowed up in the crevasses, and is thus carried down to a lower level, or even to the sole of the glacier, where it is mixed up with the material derived from the floor, both together forming the so-called *ground-moraine.* As the ice melts in its descent, moraine material becomes more and more concentrated; and finally the whole is deposited at the end of the glacier, forming a *terminal moraine*, which is usually a more or less well-defined ridge, whose form, however, depends on the configuration of the ground. Plate XIV (ii) shows a particularly clear example of a crescent-shaped terminal moraine actually in process of formation at the end of the Oberaar Glacier in the Bernese Oberland. However, the dark mounds are not entirely moraine material: a good deal of ice is also included, and the author, who may be seen in the picture standing on the middle of the glacier, had considerable difficulty in scrambling up over the slippery and unstable mixture. The picture also shows that the glacier was once much larger than now: the dark rocks at the top are not glaciated, whereas the lighter band below is lateral moraine formed when the glacier was much more extensive. The whole shows very well the characteristic termination of a diminishing and retreating glacier ending in a wide open valley: this is not very common in the Alps, where many of the largest glaciers end in almost inaccessible rock-gorges, as in the case of the Aletsch, the largest of all.

It is obvious that the best examples of crescentic terminal moraine ridges must be formed during a pause in the retreat of the front: a continuous retreat will merely leave a continuous sheet of moraine. Actual large-scale moraine deposits often form eventually a confused series of rounded humps and hollows, such as can be seen in many valleys in the Lake District.

Drainage of Glaciers.—During the summer months, and at other times when the temperature is sufficiently high, a good deal of surface melting goes on, and this often produces a considerable amount of surface drainage. This water falls down any crevasses which it may encounter, and works its way down, forming a system of streams within the ice. This kind of drainage is now generally known as *en-glacial*, in contradistinction to *sub-glacial*, which refers to drainage running on the rocky floor below the ice, and not enclosed within it. En-glacial streams seem to play a more important part in the glaciation of the high north, and will be more fully discussed in a subsequent section. The drainage of the glacier runs out in a stream at the lower end, often from a tunnel in the ice (Plate XIV (i)). The water is commonly more or less turbid or milky owing to the large amount of finely divided material, or rock flour, suspended in it.

Distribution of Glaciers of the Alpine Type.—Glaciers of the type here described occur in many other mountain regions besides the Alps, e.g. in the Himalayas, Andes, Rocky Mountains, and New Zealand; but they are not universal in all mountains which rise above the snow-line. In some cases, and especially on isolated peaks, no true glaciers occur, since the topography is unfavourable. For the proper development of a glacier something in the nature of a gathering-ground must exist; and this need can only be supplied by the occurrence of well-marked valleys and hollows among the peaks, such as are found in perfection in the Alps, but are scarce or wanting in many simple cones, such as Ararat, and many of the great volcanoes of the world. Sometimes in extinct or dormant volcanoes great accumulations of snow and ice are found within the craters: this appears to be the case in some of the higher Andes, and disastrous floods have been recorded as the result of the melting and ejection of such accumulations when dormant volcanoes have resumed activity.

Norway.—In sharp contrast with the Alpine type of glaciers are the ice-caps of Norway and Spitsbergen. Norway is on the whole a high plateau deeply dissected by fjords and their landward continuations rather than a true mountain region. The result is that masses of *névé* accumulate on the larger plateaus, and send off glaciers often in several directions from the same centre, which Alpine *névé* fields never do. Good examples are the Jostedalsbrae, north of the Sogne Fjord, and in the Hardanger region. The last-named is easily accessible, as one glacier comes down within a short walk of Finse station on the Bergen-Oslo railway, a well-known winter sports resort. This is in latitude 60° 30′ N., about the same as the Shetlands.

This type is, however, still more clearly displayed in Spitsbergen, where glaciers come down to sea-level.

Spitsbergen.—In the closing years of the last century the glacial phenomena of Spitsbergen were carefully investigated by Professors Garwood and Gregory: this work threw much light on the action of land-ice on a large scale, both at the present day and in connexion with the vanished glaciations of the past. What follows is mainly abstracted from the papers mentioned in the footnote.[1]

There are three main snowfields and from these glaciers extend down the valleys, as in Norway: on the whole each of the glaciers is very similar to those of the Alps, but there are certain important differences; most of the glaciers of the Alps have rounded or sloping terminations. but in Spitsbergen the majority end in a vertical or overhanging front,

[1] Garwood and Gregory, *Quart. Jour. Geol. Soc.*, liv. 1898, and Garwood, *ibid.* iv., 1899. These authors use the term 'ice-sheet,' for what nearly all writers call an 'ice-cap': hence some confusion has arisen in the literature. In this book ice-cap means the Norwegian and Spitsbergen type, while ice-sheet is applied to the Greenland and Antarctic type. The difference, however, is obviously only a matter of size.

This kind of termination is described in Greenland as a ' Chinese wall '. It is found in Spitsbergen that those glaciers with a Chinese wall front are advancing, while the others are retreating. The steep front is due to the more rapid movement of the upper layers, whereas in the retreating glaciers this is compensated for by the excess of melting. However, both types often exist in close proximity, as in the case of the Booming and Baldhead glaciers, so possibly some other factor is involved. There are in Spitsbergen also small glaciers of Alpine type, which as a rule have no snowfield at the head, so that it appears that under Arctic conditions snow may be converted directly into ice without pressure, and the existence of glaciers does not necessarily postulate great snowfields.

Included rock-material is extremely abundant, especially in the lower layers, and it is impossible to draw any hard-and-fast line between the ice and the underlying floor ; the so-called ground-moraine is really the lowest layers of the ice, and this ground-up material is exactly similar to much of the ' boulder clay ' of the British Isles and elsewhere. This material is clearly laid down by the glacier, but is deposited along its whole length, and not as a sort of tip-heap at the end, as is often inferred.

Iceland.—The largest ice-cap in Iceland is the Vatnajökull in the eastern part of the island, with an area of about 3,000 square miles. The southern side is easily accessible and it is clear that in spite of the small scale this shows the closest analogy to what must have been the state of affairs in large parts of North-western Europe and North America during the Great Ice Age. Since the ice-cap ends in places as much as 20 or 30 kilometres from the sea and on fairly low ground the marginal phenomena are extremely well displayed, with a great development of moraines and sandy plains, called *Sandur* in Iceland, with much melt-water on the surface of the ice and innumerable small streams wandering over the surrounding country. All this corresponds exactly with the ' outwash fans ' deposited round the margins of the Pleistocene ice-sheets, where these ended on low ground.

Greenland.—According to the estimates of the Danish explorers 85 per cent. of the surface of Greenland is covered by ice ; that is, about half a million square miles. The greater part of the coast is not now bordered by ice-cliffs, whatever it may have been in the past, but nevertheless, over long stretches enormous glaciers come down to the sea, giving rise to innumerable ice-bergs by the process known as ' calving '. Naturally, it is very difficult to ascertain what lies under the ice in the central parts, but the general opinion seems to be that the solid country is in reality, a high plateau intersected by fjords, something like Norway, although it is possible that the middle part has been depressed by the weight of the ice. At any rate no solid rock has been seen more than about 100 miles from the coast in any part of the

country, and generally the last solid ground seen in a traverse is at a much less distance from the sea. The highest point reached on the ice is not far short of 11,000 feet and generally speaking the form of the ice-sheet is like a gigantic tea-cake, with moderately steep sides soon passing into a general slope of not more than one or two degrees, while the middle is practically flat for a long distance. In the region near the coast, as also in the Antarctic, there is an enormous development of wide and deep crevasses, which renders access to the interior difficult, but in the higher parts the ice is unbroken and carries no visible rock-material.

It is only natural that at the great height of the central part extremely low temperatures prevail, even in summer, but in the coastal belt outside the ice the climate allows of a considerable fauna and flora: after all the southern point of Greenland is no further north than the Shetlands and Oslo. Even in the extreme north there is a large ice-free area with herds of musk-ox. Nevertheless, central Greenland gives us a good picture of what North-western Europe must have been like in the Pleistocene ice-age.

Until recent times little was known about the east coast of Greenland: access is always very difficult owing to sea-ice, but a good deal of exploration has now been carried out, resulting in the discovery of many high mountains in the coastal region and a complicated geological structure. All this need not be described here, since it is only with the glacial phenomena that we are now concerned. Briefly, it may be said that the Greenland ice-sheet is really an exaggerated case of the ice-caps of Norway and Spitsbergen; the central ice-field is very much larger in proportion to the glaciers that flow from it, but the principle is really the same, namely, radiation from a centre, as contrasted with the confluent ice-streams of Alpine type. The actual ice-tongues coming down through the coast-ranges are essentially similar to Alpine glaciers, though of course much larger, and they move much faster; often 50 or 60 feet a day. Owing to this rapid movement they usually have ends of the Chinese Wall type.[1]

In the older literature a great deal of space has usually been devoted to the *nunataks* or rock peaks that stick up through the ice near the coast, but they do not seem to be of much real importance. Perhaps the most significant feature is that on their landward side the ice brings up to the surface masses of moraine material, though elsewhere it is entirely free from anything of the sort: this merely proves, what is otherwise well known, that land-ice can carry material up hill. In places also, especially in the districts near the west coast, quite extensive lakes are held up by ice-barriers, which has a bearing on phenomena seen in the British Isles, to be discussed later.

[1] For an excellent short account of the glacial geology of Greenland, see Wager, *Geol. Mag.*, lxx. 1933, p. 145.

In Greenland, as in Spitsbergen, the ice shows very well-marked banding, due to shearing strains during flow, and the lower layers are heavily charged with moraine material, which is specially conspicuous in the lower parts of the Chinese Wall fronts: the ice usually shows no definite base, but merges gradually through a mixture of moraine and ice into pure moraine or boulder-clay.

Alaska.—The glaciation of Alaska presents several features of interest, and in particular it furnishes the best examples of a type of glacier not represented in the Old World. The glaciers of Alaska occur almost exclusively on the flanks of the range of mountains bordering the Pacific coast, and the great expanse of country between this range and the Arctic Ocean is of a very different type; the warm winds from the Pacific are deprived of their moisture by the coast ranges, so that here the precipitation is very great, while to the north the snowfall is small, and northern Alaska has a very strong resemblance to the great frozen plains, or tundras, of Siberia.

The coast of Alaska affords numerous examples of tide-water glaciers on a very large scale, but in their general features they scarcely differ from those of Greenland. Two of the largest and best known are the Muir and Taku glaciers. These and others in the same category give off abundance of icebergs.

The coast ranges rise to a great height, culminating in Mt. St. Elias, 18,000 feet, and Mt. Logan, 19,500 feet, the highest peak in North America. Besides the tide-water glaciers already mentioned, they give rise to hundreds, or perhaps thousands, of smaller alpine glaciers which do not reach the sea.

Piedmont Glaciers.—However, the most interesting and remarkable feature of the glacial geology of Alaska is afforded by the class of glacier to which the name 'piedmont' is applied. The upper parts of these piedmont glaciers consist of great ice-streams of the ordinary alpine type. By the confluence of several of these streams a vast mass of ice is formed, in which movement is imperceptible: in fact, the ice is usually spoken of as stagnant. If we compare ordinary alpine glaciers to rivers, by the same analogy piedmont glaciers must be considered as lakes of ice. However, this analogy must not be pushed too far.

The Malaspina Glacier.—The best-known example of a piedmont glacier is the Malaspina, on the western side of Yakutat Bay. It presents to the coast a front of some seventy miles in breadth, and its greatest extension inland is about twenty-five miles: the total area is some 1,500 square miles. It consists of three principal lobes, each of which is the expansion of one or more large alpine glaciers, flowing down from the St. Elias range. The most eastern lobe is fed by the Seward glacier, the middle one by the Agassiz glacier, and the western lobe chiefly by the Tyndall and Guyot glaciers. The Seward lobe ends in a low frontal slope before it reaches the sea, except in one place where

it forms the Sitkagi Bluffs on the coast; the Agassiz lobe is fringed by a very extensive series of moraines, as described further on, while the Guyot lobe reaches the sea and forms bold ice-cliffs. The piedmont glacier proper, as distinguished from the alpine ice-streams which supply it is a vast, nearly horizontal, plateau of ice, at a general elevation of about 1,500 feet above sea-level. In its central parts the surface is almost entirely free from moraine, but much crevassed.

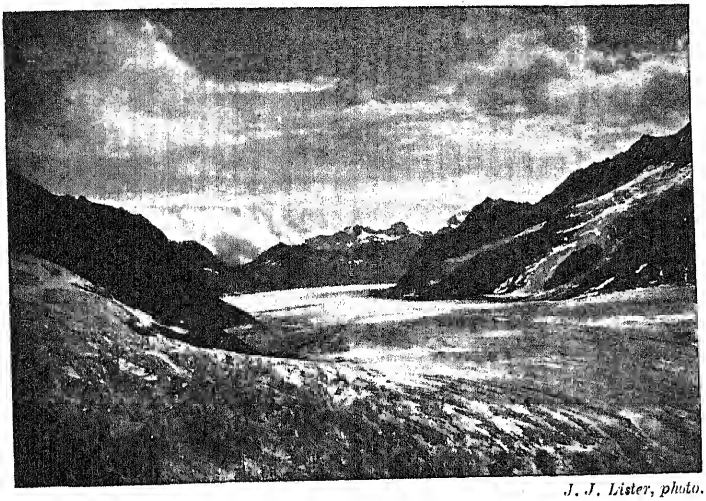
On the southern border of the Agassiz lobe are some very extensive moraines, and outside of this is a forest-belt some four or five miles wide. The forest, evidently of great age, is growing on moraine, and this moraine in its turn rests on a mass of ice, in places at least 1,000 feet thick; hence it is evident that the ice in this part can possess no appreciable movement. Beyond the margin of this forest-belt, and outside the limit of the buried ice, is also a region of dense forest growing on moraines, which form ridges and hillocks with many lake-basins. On the south-eastern side, towards Yakutat Bay, there is no forest on the ice, but moraines are very abundant, and here also there are many lake-basins in the ice.

The drainage of the Malaspina glacier is essentially en-glacial or sub-glacial, and surface streams are rare. The Yahtse river, the largest stream of the glacier, rises in the Chaix Hills, and flows through a tunnel in the ice some six or eight miles long; it issues as a stream 100 feet broad and 20 feet deep, and forms an alluvial fan covering many hundreds of acres. The Kame stream, on the east, is peculiar in that it flows for half a mile in an open channel in the ice nearly 100 feet deep. The water of these and other streams is very turbid, and they form great deposits of fluvio-glacial material in front of the ice; it is clear that a large amount of solid matter is brought down in suspension by these streams, and there must be great deposits of sand and gravel in the interglacial portions of their courses.

It appears, therefore, that the principal characteristic of the Malaspina glacier is the stagnant condition of a great portion of it, as evidenced by the growth of an ancient forest on the surface of the ice. The natural inference is that in this case the supply of ice is just balanced by the loss from melting, so that the two factors are more or less in a condition of equilibrium. It appears, however, that in the past precipitation must have been in excess to allow of the accumulation of the enormous mass of ice which now exists. Hence it is probable that a change of climate has occurred in this region.

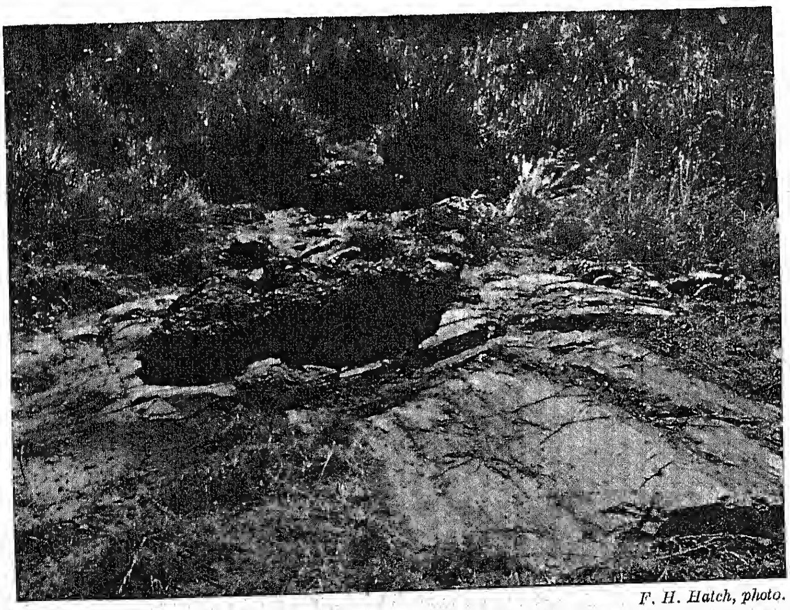
Antarctica.—By far the largest ice-sheet now existing is that around the South Pole: its general outline corresponds very roughly with the Antarctic Circle, and its total area is reckoned as about 3,500,000 square miles or seven times as large as Greenland. Its greatest height is possibly as much as 15,000 feet and the prevailing temperatures are extremely low, probably much lower than in Greenland as regards the

PLATE XV



J. J. Lister, photo.

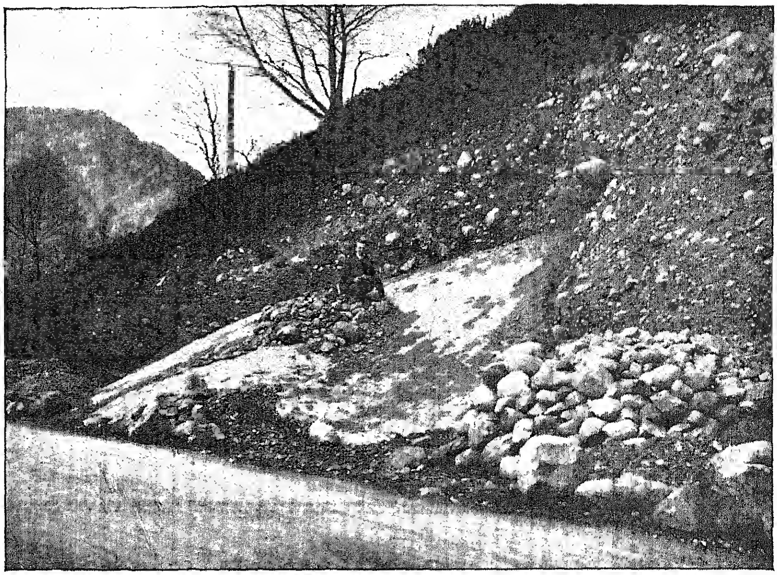
(I) ALETSCH GLACIER FROM THE EWIGSCHNEEFELD.



F. H. Hatch, photo.

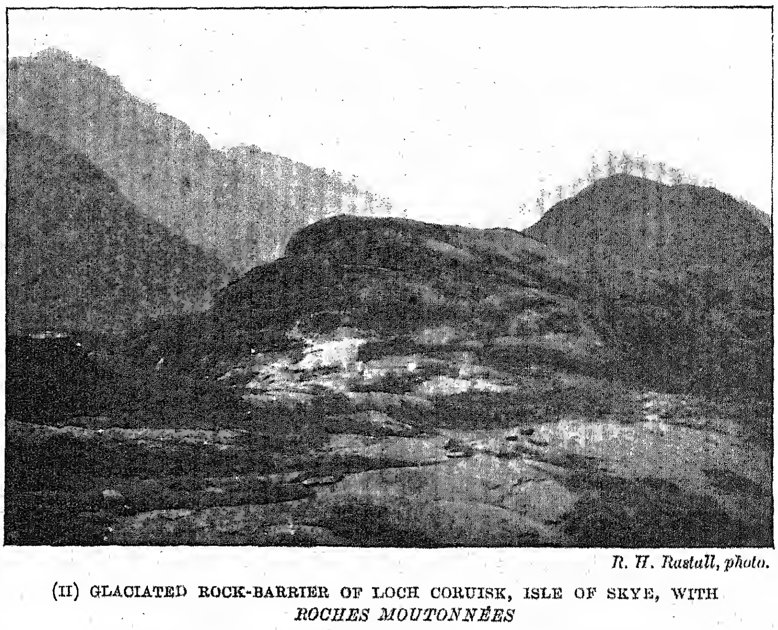
(II) GLACIATED PAVEMENT WITH DWYKA CONGLOMERATE RESTING UPON IT. MHLOGANYATI SPRUIT, NATAL.

PLATE XVI



R. H. Rastall, photo.

(I) GLACIATED ROCK-SURFACE OVERLAIN BY DRIFT. BORROWDALE, CUMBERLAND.



R. H. Rastall, photo.

(II) GLACIATED ROCK-BARRIER OF LOCH CORUISK, ISLE OF SKYE, WITH *ROCHES MOUTONNÉES*

yearly mean, since there is no summer warmth as in the northern hemisphere. This has an important effect in that the movement of the ice is thereby rendered very slow. Over the greater part of its circumference the ice-sheet ends in the sea, as an ice-barrier with a high steep front giving rise to enormous numbers of gigantic icebergs; for a great length in the Ross Sea the front of this barrier is floating many miles away from the land: in a few places only the ice stops short of the coast and sends down valley glaciers like those of the north. The best known regions are those of the Ross Sea opposite to New Zealand and Graham Land and Alexander I Land opposite South America, but it is yet uncertain how much of the known land consists of islands and how much is continental: in the Ross Sea area some very high mountain ranges of bare rock are known, up to 15,000 feet, as well as the famous volcanoes Erebus and Terror. It is probable that the ice-sheet was once even larger, perhaps several thousand feet higher, and is now shrinking. In general character the ice is very much as in Greenland, such features as crevasses, ice-falls and moraine only being developed near rock exposures, especially in the coastal regions: otherwise it is mainly an unbroken plateau of hard snow overlying solid blue ice, and owing to peculiar meteorological conditions the region is subject to violent blizzards all the year round. As may be gathered from any book on Antarctic exploration the highly broken character of the ice near the margins renders access to the central plateau extraordinarily difficult.

Transport by Glaciers.—The foregoing detailed consideration of the glaciers of several widely-separated regions shows that all display one common feature, viz. the transport of large quantities of rock-material. Where the ice-streams are surrounded by rock in situ at a higher level, much of this material is visible on the surface, having fallen from the surrounding heights, and in this case it is difficult or impossible to say how much of the material in the lower layers of the ice has a similar origin and how much is derived from the floor over which the ice moves. But in the case of continental ice-sheets—as, for example, in Greenland—surface material is absent in the central parts, since there is no rock at higher levels from which it could be derived. But when the lower layers of such ice can be examined, as for instance at the ends of the glacier-tongues, they are found to be full of moraine material; still more significant is the fact that when the ice is forced against or over any obstruction, moraines are brought to the surface: it is obvious that this material has been torn from the rocky floor by the ice itself and carried up the flanks of the buried peaks and ridges against which it impinges. It has been observed that the fronts of the Greenland glaciers always show a lower dark dirt-stained portion, and an upper layer of clear ice, which often overhangs. In many cases, both in Greenland and Spitsbergen, the amount of moraine material increases

downwards to such an extent that the glacier shades off gradually into its floor with no clear line of division, and in point of fact the supposed ground-moraine is in reality the lowest layers of the ice, which are very heavily charged with *dirt*, to use the favourite American expression.

The observations of Garwood and Gregory on the mechanics of glacier-movement in Spitsbergen are of great importance. They found the phenomena most clearly displayed in the case of glaciers with the Chinese wall type of front; the ice-stream advances by an 'over-rolling' movement; masses of ice falling from the projecting upper layers carry débris with them, and the glacier as a whole advances over the talus bank thus formed, producing a series of thrust-planes in an upward direction. By this means material can be raised to a higher level, and in one case where a glacier was advancing over a recently raised beach, material from this could be traced to a height of some hundreds of feet. This observation is significant in relation to certain features in the glaciation of Britain. One of the effects of this kind of movement is to produce distinct lamination of the ice, consisting in an interstratification of layers of dirt and ice of varying thickness; these laminae often show more or less false bedding, and this is believed to be due to shearing rather than to flow. The dirt-bands often show very marked contortion and folding, and indeed most rock-structures may be seen reproduced in laminated ice.

Transport by Glacier Streams.—Besides this transport of material by the ice itself, much solid material is undoubtedly carried along by en-glacial and sub-glacial streams. Some of this débris is doubtless deposited in the channels of the streams, both in and under the ice. The rest is carried by the streams to the ice-front and there deposited as ridges and cones of sand and gravel. It has already been noticed that streams flowing from the front of the Vatnajökull and the Malaspina glacier form great alluvial deposits and fan-like deltas by this means, and there can be no doubt that streams of these types play a very important part in glacial transport and deposition. On the recession and disappearance of the ice, they leave those characteristic deposits known as kames, eskers and åsar, which consist essentially of ridges of sand and gravel of various forms.

Evidences of Past Glaciation.—We have already seen that living glaciers give rise to characteristic accumulations at the ice-front and along the sides of the containing valleys, in the form of moraines and accumulations of débris of various kinds. Besides this, however, glaciers leave their mark on the rocks over which they pass, in the form of rounded, grooved, striated and polished surfaces. This can be seen in any region of retreating glaciers, and affords the surest indication of the former presence of glaciers in regions whence they have vanished. The surfaces over which ice has passed are rounded and polished in a manner very different from any possible effects of

water-erosion, resulting in a peculiar and easily recognisable type of topography (cp. Plate XV (ii) and Plate XVI). A specially characteristic feature is the occurrence of what are known as 'roches moutonnées,' i.e. rock masses which have been rounded off, and present a convex surface on the side from which the ice came, while the lee-side is usually quite rough and angular. Roches moutonnées are very well seen in many of the upland districts of Britain, such as North Wales, the Lake District, and Scotland, and they are associated with deposits showing all the characteristics of the moraines of modern glaciers.

Another very significant feature is the presence, often in vast numbers, of what are sometimes called 'perched blocks,' or more generally *erratics*. These have been carried, often for immense distances, by the ice and left stranded when it melted. They may be of any size from mere pebbles up to hundreds of tons in weight. Some immense ones exist in Switzerland, both in the Alpine valleys and in the low ground to the north. They are extremely abundant in Scotland, northern England and Wales and afford indications of the direction of ice-transport in the past. Only one example will be mentioned here, namely, the boulders of the very distinctive granite of Shap Fell in Westmorland, which are found by the hundred in East Yorkshire : one at Seamer station, near Scarborough, is 9 feet high.

Still more striking are certain great blocks of strata found in or overlying glacial deposits in eastern England and in Germany. Several great masses of Chalk, one nearly 500 feet long, are to be seen enclosed in glacial deposits on the Norfolk coast; at Biggleswade, a mass of Corallian (Ampthill) Clay 67 feet thick has been found, while near Ely a block of Chalk, Greensand and Gault 450 yards long and 60 yards wide has been carried a long distance and dumped in a hollow in the Kimmeridge Clay.[1] Even larger are some of the 'Schollen' of the north German plain: the biggest yet known measures 4 × 2 kilometres, or about 3 square miles.

Glaciation in Past Ages.—In this chapter we have dealt with the glacial phenomena of the present day, with incidental references to their much wider extension in recent geological times. It is well known that the glaciers of the Alps even now undergo considerable changes in size, with in many cases periods of marked advance and retreat, which not very long ago were referred to a supposed thirty-five or forty year cycle, but this seems to have broken down during the present century. Apart from these small variations it is also clear that the Pleistocene Ice Age and its present continuation did not consist of one simple and large-scale advance and retreat of the ice, or what comes to the same thing, a continuous general fall of temperature, followed by a similarly steady rise. There were pronounced fluctuations, which in western

[1] Bonney, *Cambridgeshire Geology*, 1875, p. 69, and Chatwin, *British Regional Geology: East Anglia*, 1937, p. 51.

Europe at any rate can be regarded as a succession of glacial and inter-glacial periods: in the last-named the climate was probably even slightly warmer than to-day. In the Alpine region there were four periods of maximum extension of the ice, which in at least one of them spread far into France and Germany: three of these cold periods can be traced in Germany and probably four in Britain. Details of the Pleistocene glacial deposits of the British Isles will be found in Chapter XXVI of this book.

Another and still more important fact is that ice-ages have occurred at apparently quite irregular intervals throughout geological history, from very early times, even in the Precambrian. One hitherto unexplained feature of these early glaciations is that several of them were located in what are now quite low latitudes. The best known of all is the great late-Carboniferous glaciation, represented in South Africa by the Dwyka boulder-bed, resting on beautifully ice-worn rock surfaces. In Australia five distinct glacial episodes have been established of about the same date (compare the four Pleistocene glaciations of the Alps), while in India and South America there is clear evidence of glaciation at the same time. Fossil boulder-clays (tillites) are also known in the Precambrian of Canada, South Africa and Australia.[1]

The cause of ice-ages is still one of the unsolved problems of geology.

All the characteristic forms assumed by modern moraines can be identified in any quantity in many parts of the British Isles, although of course they are now mostly grassed over, or covered by heather or bracken at high elevations. Probably the finest examples of large crescentic terminal moraines in England are two in the Vale of York: the city of York stands on one of them and the other is about 6 miles to the south, at Escrick. The L.N.E.R. station at Cromer also stands on a very large moraine.

In many districts, especially on fairly low ground, is to be seen the type of moraine known as *drumlins*. These are whale-backed ridges of almost any size, arranged in series, so that in plan they fit together in lenticular fashion. They are generally arranged with their long axes parallel to the direction of movement of the ice, though curiously enough they sometimes seem to be transverse to it. Very good examples exist in the Vale of Eden and in many parts of southern Scotland. Kames (Scotland), eskers (Ireland) and åsar (Sweden) are long and often winding ridges of gravel and sand formed by en-glacial and sub-glacial streams, either by deposition at the receding ice-front or by accumulations formed in actual tunnels in the ice and left behind on melting. One very conspicuous esker near Belfast is 12 miles long.

Ice Erosion.—During the second half of the nineteenth century there was much controversy as to the efficiency of ice as an agent of erosion. Some authorities maintained that its effects are never more than super-

[1] Coleman, *Ice Ages*. London, Macmillan, 1926.

ficial, mere smoothing and polishing of already existing forms, while others held, as the vast majority now do, that it is an agent of first-class importance in land-sculpture. The abundance of lakes in glaciated regions led some writers, especially Ramsay, to suppose that they all lay in basins which had been scooped out by the erosive power of the ice. At a later date arose a school of geologists who were inclined to deny the possibility of the erosion of a rock-basin by ice, or indeed by any other means. It was asserted that such a thing as a rock-basin in this sense did not exist; that in all cases there must be a buried outlet, or that the water was simply held up by a dam of moraine and drift; and as a result of much detailed work it has been shown that in a great number of cases this is the true explanation. But there remain a number of instances in which it is evident that the lake is everywhere surrounded by rock in situ, with no possibility of a buried channel. Such are Thirlmere, and on a smaller scale Watendlath Tarn, in the Lake District, and Cwellyn and Glaslyn in the Snowdon area. But perhaps the most convincing example of ice-erosion occurs in Skye, which has been studied in much detail by Harker.[1] The following is a summary of his conclusions:—

Ice-erosion in the Cuillin Hills, Skye.—At the period of maximum glaciation the Isle of Skye supported a small local ice-cap, which was able to repel the invasion of the Scottish ice-sheet. This ice-cap had its centre in the Cuillins and Red Hills, which formed a gathering-ground of some forty square miles in extent: the mountains were completely buried in ice, some 3,000 feet thick. The carving out of the Cuillins in its broad features was due to pre-glacial water-erosion, but the details of the relief are clearly due to ice, and this results in a peculiar type of topography. The whole surface of the mountains exhibits strongly marked rounding, striation and polishing, except on the extreme peaks, where it has been obliterated by frost weathering. Here the chemical factor in weathering is in abeyance, and only the mechanical agencies are of importance. Consequently, the conspicuous features are carved out almost irrespective of the lithological character or physical structure of the rocks, and the Law of Structures does not apply. Rocks of very varying degrees of hardness are ground down to one uniform plane or curved surface.

The tendency of ice-erosion is to produce a simplification of valleys in ground-plan and cross-section; spurs are destroyed, curved reaches straightened, and subsidiary ridges planed away; the floor of the valley is widened, and the walls become straighter and steeper. But with regard to the longitudinal section the above considerations do not wholly apply.

In many cases the thalweg of the valley is not a uniform concave curve, as in mature rivers; but ice-erosion tends, within certain limits,

[1] Harker, *Trans. Roy. Soc. Edinburgh*, vol. xl., part ii, p. 221.

to accentuate inequalities, instead of levelling them up. So long as the upper surface of the ice has a downward inclination, the amount of erosion varies directly as the thickness of the ice, since it depends on the pressure acting on the floor. If this floor is irregular the ice will be thicker over any hollows, and will tend to deepen them. This process has produced some true rock-basins, which contain lakes of considerable size. The best example is Loch Coruisk, about 1½ miles long and one-third of a mile wide. Soundings show that it consists of two deep hollows separated by a ridge, which bears several small islands. The surface of the water is about 25 feet above sea-level, and the depth

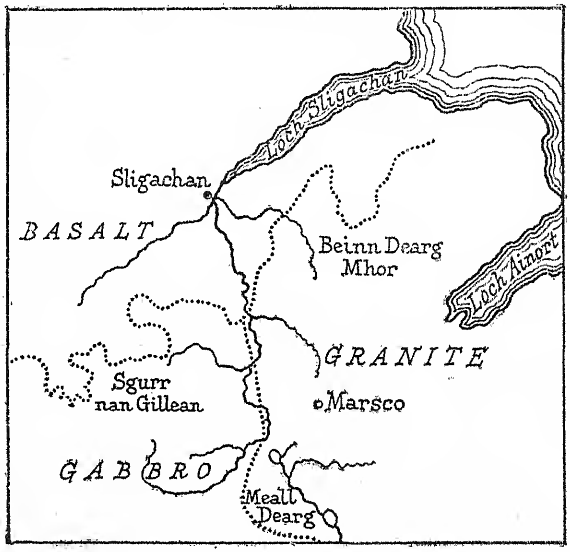


FIG. 48.—MAP OF THE SLIGACHAN VALLEY.
(After Harker, 'Tertiary Igneous Rocks of Skye,' *Mem. Geol. Survey*, 1904.) Scale, ½ inch to 1 mile (slightly diagrammatic). The dotted lines show the boundaries of the different rocks in place.

of the lower basin is 125 feet, so that it descends 100 feet below sea-level; the upper basin has a maximum depth of about 90 feet. The whole is visibly surrounded by rock, except for a gravel-flat at the head, and the bottom consists of bare rock. In the Camasunary valley are two smaller lakes of a similar kind.

The evidence of erosion afforded by the distribution of boulders in the Sligachan valley is very striking. The eastern side of this valley in its upper part consists of granite, the western of gabbro; the lower part of the valley passes over basalt. In the upper part nearly all the boulders on the right side of the central line of the ice-stream, which practically coincides with the junction of the two rock types, are of granite, while on the left an equally large proportion are of gabbro (see

Fig. 48). So soon, however, as we cross the line dividing these rocks from the basalt, boulders of the latter rock make their appearance in gradually increasing numbers, till in a short distance they form the great majority. It is clear that here the boulders are fragments of the country rock, which have been torn from their bed and carried along by the ice-stream. The transport is therefore solely in a downward direction, and boulders of basalt are never found at a higher level than the same rock in place.

Topographic Forms due to Glaciation.—Besides the superficial features already described there are also topographic forms on a much larger scale, characteristic of glaciated areas, and best seen in regions whence the ice has vanished. Some of these will now be described.

(1) *U-shaped Valleys.*—The cross-section of a valley due to water erosion alone is commonly V-shaped, with uniformly sloping sides, while in plan it is generally zigzag, with alternating spurs. Glaciated valleys on the contrary when deeply incised are characteristically U-shaped in cross-section, straight and without any projecting spurs.

FIG. 49.—CROSS-SECTION OF AN OVER-DEEPENED VALLEY. THE CURVE IS TRACED FROM A PHOTOGRAPH OF THE ROMSDAL, NORWAY.

Moreover, at some definite height the slope of the sides becomes suddenly less steep, so that the cross-section is like a U within a V (Fig. 49.) The explanation is that the wide upper part represents what remains of the old pre-glacial valley, due to river erosion, which has been over-deepened and straightened by a glacier. The level where the change of slope occurs represents the top of the ice: below this the sides of the valley are smoothed and often polished; above it are the rough frost-shattered peaks.

(2) *Hanging Valleys.*—Reference has already been made to one kind of hanging valley, consisting of a step or steps in the course of a main river: this often happens also in glaciated regions, but much more characteristic is another case, where tributary valleys suddenly become much steeper on joining the main valley, their streams often descending as waterfalls. This is extremely common in over-deepened U-valleys, as just described. The upper lines in Fig. 49 may be taken as representing the thalweg of such streams, except that they do not generally occur opposite in pairs, but alternately.

(3) *Truncated Spurs.*—From what has been said in the last two paragraphs it follows that the ends of the original spurs of the V-valley must remain on the sides of the U-valley in a much shortened state: this is difficult to make clear in words, but easy to visualize or to read off a contoured map. In the ideal case the ends of the truncated spurs are triangular and slope steeply backwards: in fact, they actually form the walls of the U-valley between the tributaries, and therefore they also are not usually opposite in pairs, but alternate, between the hanging side-valleys.

There are innumerable examples of the three features just described in almost all glaciated regions: on the grandest scale in the Alps and in the fjords of Norway; smaller but equally effective in the British Isles, especially in the Lake District. The upper part of Borrowdale shows them extremely well, while the south front of Saddleback above the Keswick-Penrith road consists of four immense truncated spurs, as may be easily seen on a contoured map.

(4) *Cirques.*—Another striking feature of glaciated regions, which has not been quite satisfactorily explained is afforded by those great armchair-like hollows among mountains, to which so many names are applied in different countries: *corries* in the Highlands; *combes* in the Lake District, *cwms* in Wales, *cirques* in the Pyrenees, *Karen* or *Karren* in Germany, *botner* in Norway. Such hollows occur on all scales and are a very characteristic topographical form. An excellent small scale model may be made by sitting down in a bank of soft snow. For most purposes *cirque* is the most convenient name, and it does convey an idea of the form, the more or less semi-circular plan of the contour lines being the main point: also the back slope is concave upwards, the steepest slope being at the top, where there is often an actual precipice. One of the finest examples in the British Isles is the great hollow on the east side of Helvellyn, where Red Tarn lies between the two sharp ridges of Striding Edge and Swirrel Edge, which are almost equally steep on the outer and inner sides and very narrow at the top. One of the most famous of all is the great Cirque de Gavarnie in the Pyrenees.

A very common feature is a lake at the bottom of the hollow, which implies a barrier of some sort, either rock or more often a crescent-shaped moraine: this might be formed by scree-material sliding down over snow that once filled the hollow. But the actual origin of the hollow is much more difficult to explain. There can be no doubt that it is in some way due to ice-action. The existence of a slight hollow seems to be essential as a primary condition, but when such a hollow became filled with any considerable quantity of ice-forming snow the rest of the excavation may be due to the so called 'plucking' effect of ice, which seems to consist in alternate freezing of the ice to the rock in winter, and downward movement of the ice in summer, pulling away

blocks of rock. It has also been suggested that the presence of a *bergschrund*, a great gap at the surface between ice and rock, has something to do with it. If plucking is the cause, the effect would obviously be cumulative, becoming more effective as the hollow deepened.

It has been noticed that cirques are more numerous and larger on the east and north sides of mountains, where glaciation is more intense: even now great masses of snow often linger very late in spring on the east side of the Helvellyn range, while the west side is quite free from snow, and no doubt during the Ice Age the difference was also marked. In the latitude of Britain, which has no great elevations, there must even then have been a good deal of difference between summer and winter temperatures. It may be said that the secondary effects of glaciation are more clearly seen in regions from which the ice has departed than where it is still present to hide its own work, and the study of the glacial phenomena of Britain and North America has done much to elucidate the details of modern glacial action.

Glacier Lakes.—Lakes of various kinds are a very common feature of glaciation, and may be formed in various ways. The origin and character of the lakes which are so abundant in regions of vanished glaciers is treated elsewhere, and it is only necessary to consider here lakes associated with contemporaneous glacial conditions. During seasons of rapid melting pools of water frequently collect in hollows on the surface of the ice; but these are usually short-lived and of small importance, since they are commonly drained off by crevasses. When two ice-streams join a lake is frequently formed in the angle between them, lying partly on the ice and partly on rock. A well-known example is the Lac de Tacul between the Glacier du Géant and the Glacier de Leschaux in the Mont Blanc region and there is a small one at the foot of Monte Rosa between two branches of the Gorner Glacier, well seen from the Gorner Grat. The water of such lakes is usually of a peculiar greenish blue colour. The Danish explorers in Greenland have described curious small circular lakes in the hollows on the lee-sides of nunataks, often surrounded by high cliff-like walls of ice. One such has a diameter of over 250 yards.

A glacier coming down a tributary valley may hold up the drainage of a main valley and form a lake. This is not common except in a temporary way, since such ice-barriers are soon destroyed. A remarkable case is that of the Vernagt glacier in the Tirol, which periodically extends itself enormously at a very rapid rate; it comes down a steep side valley, the movement being partly ordinary glacial flow and partly an ice-fall, and sometimes forms a lake nearly a mile long and 300 feet deep. Similar phenomena are known in the Caucasus and Himalayas. Such lakes are short-lived, since the barrier either bursts suddenly and causes disastrous floods, or is slowly washed away by melting and current action.

A more important case is where the drainage of a tributary stream is obstructed by ice in the main valley. Perhaps the best example of this is the oft-described Märjelen See at the elbow of the great Aletsch glacier (Plate XVII (i)).[1] This is peculiar among glacier lakes in that it possesses a maximum level beyond which it can never rise, since at the head of its valley is a low col, leading over into the valley of the Viesch glacier. This may give rise to a definite beach at the level of the col, and this observation has an important bearing on the origin of certain phenomena in Britain, hereafter to be described.

Many of the ice-streams descending from the inland ice of Greenland block up tributary valleys and produce lakes of this kind on a very large scale. The lake of Tasersuak, on the west coast of Greenland, is some 12 miles long by about $2\frac{1}{2}$ miles broad. It is in reality a fjord dammed by the great Frederikshaab glacier; on the other side of the same glacier is another corresponding dammed valley, and this phenomenon is not uncommon in that region. Lakes of this type are of particular interest, because some peculiar topographical features in the north of England and Scotland are explicable on these lines.

The Parallel Roads of Glenroy.—The celebrated Parallel Roads of Glenroy, Inverness-shire (Plate XVII (ii)), are narrow terraces or beaches 40 to 50 feet in width, running horizontally along the mountain slopes; they consist chiefly of angular detritus of local rocks. They occur at heights of 1,153, 1,077, and 862 feet respectively, which correspond exactly with the levels of three cols—one at the head of the main glen, one in a tributary glen, Glas Dhoire, and one at the head of Glen Laggan, into which the lowest 'road' passes. At the time of greatest advance of the ice, the drainage of the valley was blocked till it overflowed into the Spey basin over the high col at the head of Glenroy. As the ice-front withdrew southwards the lower cols were successively uncovered, and the water-level remained sufficiently long at these levels to form distinct beaches, the present 'roads.' They were formerly held to be ancient sea-beaches formed during a period of submergence, but this view is now universally abandoned (see Fig. 50).

Glacier Lakes in Northern England.—In the highly glaciated area of northern England evidence has been brought forward by Kendall, Dwerryhouse and others, showing the existence of a highly developed system of glacial lakes, due to the damming of river valleys by great glaciers, and in particular by the North Sea glacier, and those of the Eden valley and Teesdale. It is here necessary to anticipate part of our description of the glaciation of Britain, which will be found in the stratigraphical part of this volume. However, without entering into detail, we may say that local glaciers passed from the drainage basin of

[1] In Plate XV (i) the Märjelen See lies at the sharp bend of the glacier, on the left, but the low col leading to the Viesch valley is hidden by the very black spur in the middle distance.

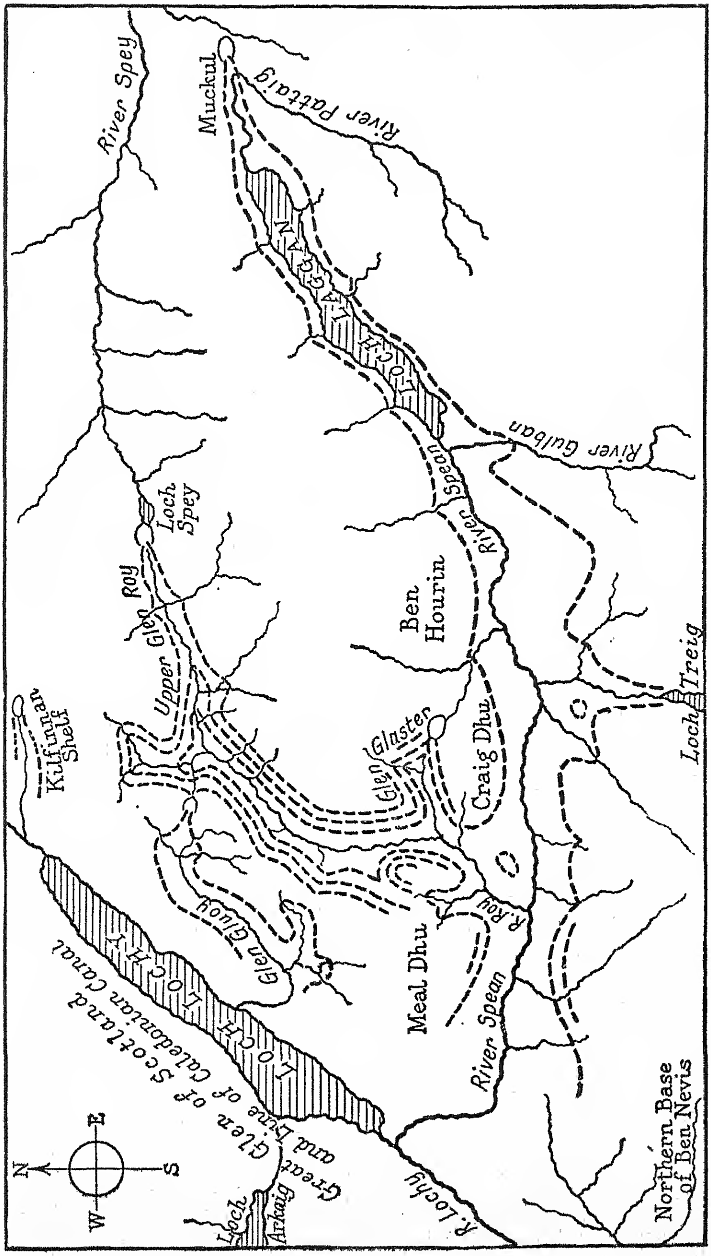


FIG. 50.—DIAGRAMMATIC MAP OF THE PARALLEL ROADS OF GLENROY. (After Lyell.)

the Irish Sea over the Pennine chain into the valleys of the Tyne, Wear, Tees and other eastward-flowing rivers; also the North Sea was filled by a great mass of ice, derived from various sources, which encroached on the north-east coast, blocked up the mouths of the valleys, and was forced inland, often for a considerable distance, by the pressure behind.

A great mass of ice from the Lake District and the Solway basin, carrying many characteristic boulders, was forced up over the Stainmoor Pass and blocked up the upper part of Teesdale, forming large marginal lakes of the Märjelen type, which have left abundant traces behind them. Local glaciers also flowed down the eastern slope of the Cross Fell range, by the valleys of the Tees and Wear. One of these glaciers blocked up the valley of the Maize Beck and formed a large lake, which probably drained over High Cup Nick on to the surface of the Edenside ice, which here stood at a lower level. The Solway ice also flowed down Tynedale and held up many lakes in the valleys of the Allen, Devil's Water and Derwent. All these lakes formed overflow channels of a peculiar character, which will be described in detail later on.

Turning now to the Cleveland district in N.E. Yorkshire, we find that the great North Sea ice-mass was forced in upon the coast, and penetrated inland for a distance of several miles; the Cleveland Hills, though rising to a height of over 1,400 feet, possessed no local glaciers, but along their northern slopes the ice rose to a height of some 1,000 feet above sea-level. This ice over-rode the watershed to the north of the Esk valley at a height of about 750 feet, and blocked up this valley at several points, corresponding to comparatively low cols in the northern watershed. At the period of maximum extension the lower part of the valley was completely blocked and all drainage to the sea was prevented. The water of the river system, together with great volumes from the melting margin of the ice, accumulated till it formed a great lake, occupying the whole of Eskdale and its tributary valleys above Grosmont to a height of about 725 feet. This, which is called by Kendall 'Lake Eskdale,' was about eleven miles long, and at least 400 feet deep (see Fig. 51).

Since all direct outflow to the sea was prevented, the water accumulated till it found an outlet elsewhere. In this case the outlet was found over a sharp spur separating Eskdale proper from the valley of a southern tributary, the Murk Esk, and over this spur the water flowed in enormous volumes. This rapid flow produced great erosion, and soon cut a conspicuous notch in the spur. As the ice retreated or melted away this process was repeated at a lower level, and the spur in question shows a series of parallel notches one below the other, corresponding to pauses in the retreat of the ice. These notches are the 'overflow channels' of Kendall, and they show a very characteristic form; they always possess a flat floor and very steep sides, giving a conspicuous U-shaped section. They occur in large numbers all over the glaciated

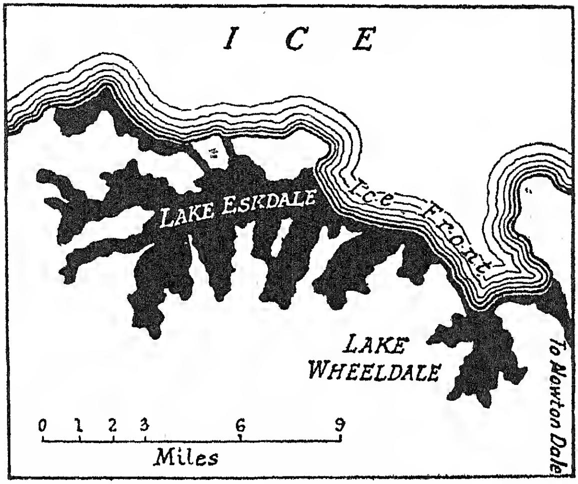


FIG. 51.—MAP OF LAKE ESKDALE AT ITS MAXIMUM EXTENT. (After Kendall.)

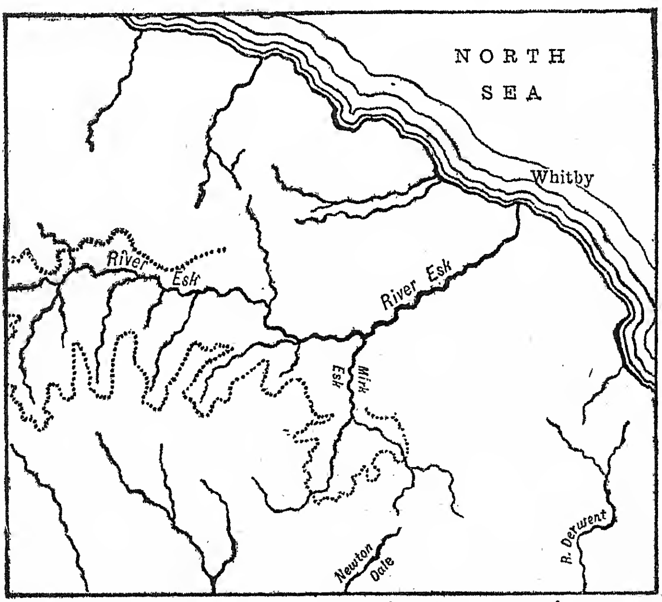


FIG. 52.—THE PRESENT DRAINAGE SYSTEM OF ESKDALE.
The dotted line indicates approximately the maximum extension of the glacial lakes. Scale, 4 miles to 1 inch.

areas of the north of England, and most of them are now quite streamless.

The water from Lake Eskdale eventually found its way over a col at the head of a valley flowing down towards Pickering, which it greatly deepened and enlarged, forming the magnificent gorge of Newton Dale, through which the railway from Pickering to Whitby now runs. The highest point of the rocky floor of this valley is at 525 feet above sea-level, so that when the overflow stream had cut down to this point the lake had evidently found an outlet elsewhere, presumably owing to the retreat of the ice in the lower part of Eskdale, which had opened a direct channel to the sea, past Whitby (Fig. 52).

The encroachment of the North Sea ice also brought about remarkable changes in the course of the Yorkshire Derwent. In pre-glacial times the wide Vale of Pickering, extending westwards from the coast south of Scarborough, was drained by a river which probably flowed into the sea near Filey. The North Sea ice extended some seven or eight miles inland and converted this region into a lake. The water accumulated until it reached the top of a col south of Malton at an elevation of some 250 feet; it then proceeded to carve out the great gorge in which Kirkham Abbey is situated, and which still forms the channel of the Derwent. The original valley is blocked at Filey by a barrier of drift about 150 feet high, and the main river, which collects the drainage of the moorlands to the north, now flows almost due west from Ganton towards Malton, cuts through the southern escarpment, and flows into the Ouse drainage basin. Thus as a direct consequence of glaciation we have the remarkable result that streams which rise not more than two or three miles from the sea, near Robin Hood's Bay and Ravenscar, and others rising within a mile of the sea, south of Filey, finally flow into the Humber, after a course of nearly a hundred miles. There is no stream of any consequence flowing into the sea anywhere on the long stretch of coast, about 75 miles, between Whitby and Spurn Point.[1]

The Lithology of Glacial Deposits.—It will be well to give here a very brief description of the lithology of glacial deposits, as they do not fit well into the general classificatory scheme of sediments in Chapter IX. Some of the most important are those formed by melt-water flowing on, in or under the ice and over the ground in front of a glacier, especially during its retreating stages (outwash fans, etc.). These are, of course, somewhat similar to the deposits formed by normal rivers, the chief difference being in the usually less rounded form of the component fragments and the less efficient sorting. Good examples are afforded by the innumerable varieties of gravel and sand of glacial origin in East

[1] Kendall and Wroot, *Geology of Yorkshire*, 1924, p. 491.

Anglia. Here, however, it is often very difficult to decide to what extent the original deposits have been resorted and otherwise modified in inter-glacial and post-glacial times, and the whole story is obviously very complicated. When glacier-fed streams run into lakes, or reach low flat stretches of country they lay down beds of sand and mud, the last-named often almost white, from the fineness of the material.

It is not at all easy to give an intelligible general account of moraine material, as it may consist of almost anything, and when directly deposited by melting ice, without the intervention of water transport and sorting, fragments of all sizes may be mixed up together, since in a terminal moraine some of the material may fall off the top of the ice, some of it has been carried along inside, and some is extruded from the bottom : this last may have undergone much grinding and crushing. Lateral moraines are essentially the same as scree, and therefore all types consist mainly of angular and sub-angular rock-fragments. One of the most characteristic features of moraines is the presence of facetted, scratched and more or less polished stones, but it must not be supposed that these are always present : there is no reason, for example, why they should be found in lateral moraines ; they are only formed in the lowest layer of the ice, in contact with a hard rock floor.

True boulder-clay, which is so characteristic of the Pleistocene glacial deposits, and constitutes the ancient tillites, is not known in the Alps, but it is known in Spitsbergen and Greenland. It consists of a matrix of clay, often very stiff indeed, enclosing an extremely variable proportion of blocks of rock of any size, from mere chips and pebbles to masses weighing many tons, and often showing the characteristic facetting and scratching. It is by means of these that the glacial origin of the ancient tillites has been established.

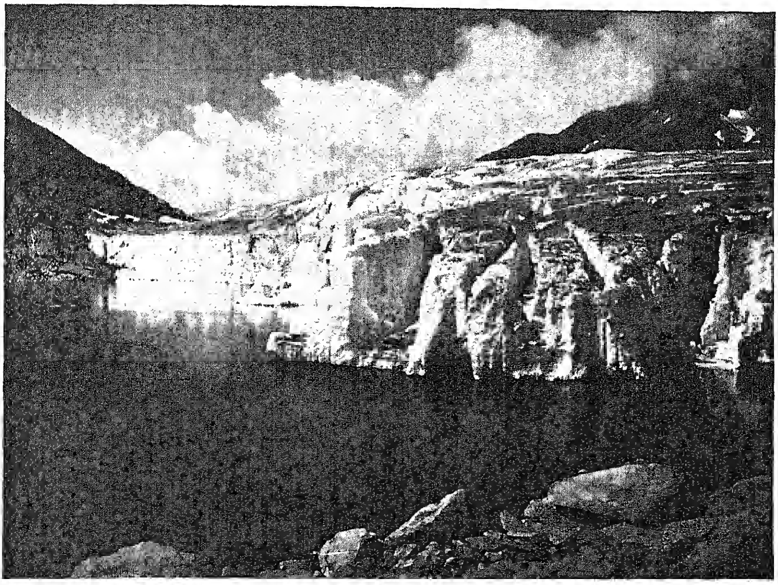
When, as has often happened, sub-glacial streams from retreating ice-sheets run into lakes held up by moraines the finer material held in suspension is deposited in the still water. Since melting is much more active in summer the streams are then larger and carry coarser material than in winter : the result is the formation of well-laminated clays and silts, each pair of coarser and finer layers forming a year-ring as in a tree. There may be many laminae in an inch. By an elaborate system of counting and plotting the laminae in these *varve-clays* over large areas, too complicated to describe here, it has been found possible to estimate the time elapsed during the retreat of the ice over Southern Sweden, and so to date the end of the Great Ice Age in that region, which works out at about 12,000 years ago.

A very common and characteristic feature of glacial deposits is an extremely confused structure, with rapid variation in size and character of components both vertically and horizontally : thus wisps of sand are often enclosed in gravel, and vice versa, and both in boulder-clay. Current-bedding is also common and among the stratified deposits a

high degree of contortion is often displayed, simulating many structural types found among the highly folded ancient rocks. This may be due to either of two causes : actual thrusting by ice moving over or against the deposit or by melting of originally enclosed blocks of ice, leading to collapse of the bedding : slumping and creep of material during summer melting of gravels frozen solid in winter has led to the formation of the so-called Taele gravels. It is not uncommon to find in well-stratified glacial sands and gravels laid down in water, large boulders which must have been dropped by floating ice. This also happens in the case of marine sediments laid down in such regions as the Newfoundland Banks, where icebergs are common.

It may also be mentioned here, for want of a more suitable opportunity, that in several instances disturbances in old and more or less solid rocks really due to the impact of ice-sheets have been mistaken for the effect of tectonic earth movements.

PLATE XVII



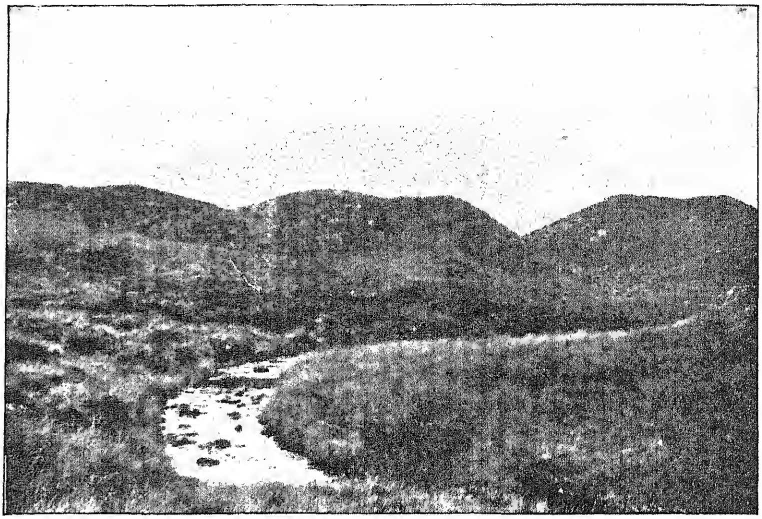
J. J. Lister, photo.

(I) ICE CLIFFS OF THE MÄRJELEN SEE.

British Association photo.

(II) THE PARALLEL ROADS OF GLENROY.

PLATE XVIII



J. Romanes, photo.

(I) MORAINE BARRIER OF LOCH SKENE, MOFFATDALE.

J. Romanes, photo.

(II) GLACIATED ROCK BARRIER OF LOCH CORUISK, ISLE OF SKYE.

CHAPTER VII

LAKES

Definition of a Lake.—It is a matter of considerable difficulty to frame a definition of a lake which will cover all possible cases, since their manner of origin shows very wide variations. Perhaps the simple statement that a lake is a hollow filled with water is the most satisfactory, although even in this the element of size has to be taken into consideration. The term lake is applied in ordinary language to a sheet of water of considerable extent, whereas the smaller bodies of water are distinguished as tarns, meres, pools and puddles. The term pond in this country is generally restricted to artificial structures, though in America this distinction is scarcely applicable.

It is of some interest to note that lakes of most types are not usually long-lived features. Very often they are either drained or more commonly filled up within what is geologically a short time. Traces of vanished lakes are innumerable on the present land surface and during historic times many shallow lakes in civilised countries have been drained and converted into agricultural land, which is often very fertile. In the most recent times, on the other hand, many artificial ones have been created, under the name of reservoirs, both for water supply of towns and on a rapidly increasing scale for hydro-electric power in mountain lands.

Although in these cases the dam is artificial, nevertheless, in many of their features these man-made lakes simulate the geological characters of natural ones, for example as regards the forms of their shore-lines. When the Manchester Corporation took over Thirlmere in the Lake District and raised its level considerably, within a surprisingly short time the crudities of the newly drowned shore-line were softened down by the development of very natural-looking beaches. This is of interest as showing that in some instances geological processes are rapid in their working.

The origin and character of several different kinds of lakes have already been dealt with, either incidentally or at length, and the present chapter is to be regarded partly as a summary. Detailed descriptions will be given only of types not before dealt with, and for the others reference will be made to the preceding pages.

As before stated lakes are due to a large number of very different causes, and it is not easy to draw up a simple classification, but the

following four groups include at any rate the vast majority: the last-named is, however, much less important than the others.

1. Lakes held up by a dam or barrier.
2. Lakes due to erosion (including solution).
3. Lakes due to earth-movement.
4. Crater lakes.

It must also be understood that lakes may be due to a combination of the above-mentioned causes: as will be seen later a lake lying in a basin due to erosion may be made larger and deeper by the accumulation of a natural barrier, just as some have been enlarged by artificial dams.

Barrier Lakes.—From this class we exclude those cases in which the barrier is due to earth-movement, since this kind of barrier consists of the same material as the rest of the basin. The barriers in the sense here employed consist of transported material which has blocked up the course of a river or in some other way caused the formation of a basin-shaped hollow. They are, in fact, natural dams. Some lakes of this class are very temporary phenomena.

One of the commonest causes of a short-lived lake is the descent of an avalanche of snow or ice from a glacier across the course of a river. Behind this the water accumulates till it either overflows the dam or bursts through. In the latter case the destruction brought about in the valley below is often very widespread. Examples of this are not uncommon in mountain regions like the Alps or the Himalayas. Sometimes the rapid advance of the front of a glacier without any actual discontinuity may produce a somewhat similar effect, though generally of a more lasting character. In mountainous districts temporary lakes may also be formed by rockfalls and landslips, and even by mud-flows. Of a slightly more lasting character are glacier-lakes in the strict sense, which have been fully dealt with in the previous chapter. Although their duration may be long as measured in years, they cannot be considered permanent in the geological sense, since they are liable to be altered by any disturbance of the glacier to which they owe their origin. A good example of this is afforded by the well-known Märjelen See, which empties itself more or less completely nearly every summer. It is obvious that only under special circumstances can such transitory and variable lakes show any definite shore-line or beach. Reference should here be made to the account of the Parallel Roads of Glenroy given on p. 116.

Many of the most important lakes of the British Isles and elsewhere are directly due to the formation of moraines and deposition of drift in river-valleys during the glaciation of the country, and indeed the connexion between glaciation and lake-formation is very close. All the larger sheets of water in the English Lake District, with the excep-

tion of Thirlmere, are believed to possess drift-barriers.[1] Nevertheless, since some of them, for example Windermere and Wastwater, the deepest of all, descend below sea-level, it is difficult to avoid the conclusion that they lie partly in rock-basins, though the present high level is due to moraines. Others, such as Derwentwater and Bassenthwaite are very shallow and can be explained as wholly due to moraine barriers. There is a special peculiarity about the outlet of Windermere, in that it does not drain out in the obvious way down the broad straight Cartmel valley, which is its direct continuation, but the river cuts sharply through a ridge in a S.W. direction in an extremely narrow valley, which is quite out of scale with the river running through it. The reason for this is not clear.

The origin of most of the smaller tarns of the Lake District, North Wales and the Highlands is also to be attributed to moraines, and in particular the small, more or less circular tarns which so commonly occur in cirques, cwms and corries are nearly always held up by a crescent-shaped moraine, probably formed when the cirque was filled by snow or ice during the Glacial period.

It is not uncommon for the lowest part of the course of a river in the immediate neighbourhood of its mouth to be converted into a lake by the accumulation of a high beach of shingle (storm-beach). By this means the stream is ponded back and an expanse of water is formed which may be either salt or fresh according to whether or not it is invaded by high tides. This subject trenches closely upon the province of beach accumulation and marine deposition (see p. 139) and need not here be further pursued in general terms. There is, however, in Britain one very important case, that of the Norfolk Broads. In former times a river flowed through Norfolk with a wide estuary opening into the sea to the north of Yarmouth. Now the prevailing set of the tides and currents along this coast is from the north, and they bring with them much material from the destruction of the soft strata of Yorkshire and Lincolnshire. This material formed a spit, which eventually blocked up more or less completely the mouth of the river, and inside this barrier great sedimentation took place in a somewhat irregular manner, leaving areas of water and a complicated network of channels connecting them: these are now the characteristic features of this district. The silting up of the estuary has been assisted to a great extent by the luxuriant growth of rushes, sedges and other water-plants, which act partly by checking the movement of the suspended matter in the water and causing it to settle down, and partly by the decay of their own vegetable substance.

In the south-west of England there are several examples of what may be called coastal lakes of analogous origin. Perhaps the best known

[1] Mill, *Geogr. Journ.*, vol. vi., 1895, pp. 46, 135 (published separately under the title *The English Lakes, Results of a Bathymetrical Survey.* London, 1895).

is the Fleet, a very narrow lagoon about 8 miles long held up behind the Chesil Beach, west of Portland Bill (see p. 141). Of very similar type, but smaller, is Slapton Ley, between the Start Point and Dartmouth. The little Swan Pool at Falmouth is held up by a storm beach, as is also the very picturesque Looe Pool at Penrose, near Helston, in Cornwall; here, although a stream runs in at the top, there is no visible outlet, and the drainage apparently soaks out through the beach.

Somewhat analogous to the foregoing is a phenomenon occasionally seen in regions where sand-dunes are a prominent feature. In the south-eastern angle of the Bay of Biscay, in the district known as the Landes, the advance of sand-hills is sometimes so rapid that the streams are unable to carry away the sand blown into them, and become choked. By this means lakes may be formed, but they are not of much importance.

In hilly regions, where the growth of peat is highly developed, it is not uncommon to find small tarns formed by its agency, and curiously enough these tarns are frequently situated on the cols between adjoining valleys. The reason for this peculiarity is not very clear, but it is probably connected with the outward growth of the peat in all directions from a centre. Sometimes where large expanses of peat exist at high elevations they may be much exposed to wind, and during dry periods much material may be blown away, forming hollows which afterwards become filled with water. The margins of these peat-formed lakes often show on a small scale an almost complete imitation of wave-cut coast-lines.[1]

Lakes due to Erosion: Rock Basins.—Rivers cannot form lakes of any size by simple erosion: the depth of possible excavation is only that of the river itself, except in the unimportant case of deep pools at the foot of waterfalls, and as already explained a meandering river fills in behind itself. Therefore lake-basins lying in solid rock without alluvial or glacial barriers have to be explained by some other agency.

From the abundance of lakes in glaciated areas it was long ago suggested, especially by Ramsay, that most lake-basins were excavated by ice. Later there arose a school of geologists who denied that ice could erode a rock basin of any considerable size, but now the great majority are agreed that it can. One very clear case, in Skye, has already been described (p. 112), and as this question will come up again in connexion with fjords (Chapter VIII) it will not be discussed here, but taken for granted. But it is well to emphasise that there is a very close connexion between fjords, rock-basins and glacially modified valleys.

It has already been noted that Thirlmere has no barrier, but as was abundantly proved during the construction of the dam, the outlet was entirely over rock, and there is no possibility of a drift-filled channel,

[1] Rastall and Smith, *Geol. Mag.*, 1906, p. 406, with figure.

such as has actually been found in some other lakes. The little Watendlath Tarn, above Lodore in Borrowdale, is also a rock basin.

There are in Scotland many large lakes of great interest from this point of view. Loch Lomond, the largest of all, seems to be partly a barrier lake and partly a rock basin, like Windermere. It is highly significant that the deepest part, about 630 feet, is in a very narrow stretch in the upper part of the lake, nearly opposite Tarbet, where ice travelling down the valley would be hemmed in and piled up high. The wide lower part is quite shallow, with islands. Loch Tay, which is also long and narrow, goes well below sea-level, though it is in the middle of the country. The chain of long deep lakes, Lochs Ness and others that form the greater part of the Caledonian Canal, probably owe their existence in part to the great fault that stretches from sea to sea, and doubtless made ice-erosion easy along its shatter belt; earthquakes are not uncommon along this line. One of the most interesting is the comparatively little known Loch Morar, in Inverness-shire, between Arisaig and Mallaig. It is about 10 miles long and although the outlet is close to the sea and only about 30 feet above high-water mark, the greatest depth is over 1,000 feet. The outlet is visibly over solid rock and the lake obviously lies in a rock basin, such as could only have been excavated by ice.

A point of special interest, which can only be appreciated on a fairly large scale map, is the remarkable resemblance in plan of the fresh-water lochs and the sea-lochs (fjords) of Western Scotland: they are obviously due to the same cause. Two of them, Loch Etive, near Oban, and Loch Leven at Ballachulish, are according to strict definition fjords at high tide and lakes at low tide, the rock barrier lying between high and low water mark, so that at low tide the outfall is a waterfall or rapid.

Large-scale basins capable of holding water may also be formed by solution, especially in some of the softer though consolidated rocks, in much the same way as lake-basins, usually small, are sometimes produced by melting of large masses of ice enclosed in glacial deposits. As already pointed out, certain rocks, e.g. limestone, dolomite and beds of gypsum and rock-salt, are soluble, and their removal by this means may give rise to hollows, which become filled with water. It is believed that some of the lakes of the Alpine region, e.g. the Ticino valley,[1] have been formed in this way, since such comparatively soluble rocks here occur in patches intercalated with the less soluble ones, and the lakes often lie along the strike of beds of dolomite, gypsum, etc. Again, such beds existing underground, though not exposed at the surface, may be removed by solution, so that the overlying strata sink, thus forming hollows such as some of the meres of Cheshire. This process may readily be mistaken for differential earth-movement of tectonic

[1] Garwood, *Quart. Journ. Geol. Soc.*, vol. lxii., 1906, p. 165.

origin, and its true nature is difficult to prove. Analogous to this is a phenomenon sometimes seen in limestone regions, where the collapse of a cave with an underground river may give rise to a long, narrow, and possibly winding sheet of water, especially if the exit is blocked by the falling in of the roof. The temporary or permanent blocking of a swallow-hole might have a similar result. In some of the great caves of limestone regions, underground lakes are a not uncommon feature.

Lakes due to Earth-Movement.—This class is of particular interest and importance, since it includes some of the largest detached bodies of water on the surface of the globe. In conformity with the special conditions, such lakes may be either salt or fresh. Excellent examples of the former kind are afforded by the Caspian Sea, the Sea of Aral and some smaller salt lakes in South-western Asia. The level of the water in the Caspian is now 84 feet below that of the Black Sea, while that of the Sea of Aral is 128 feet above the same datum line. It is believed that they were once continuous, since banks of shells of species now living in the Caspian extend widely over the area between it and the Sea of Aral. It is, however, doubtful whether they were connected with the Black Sea, since the seals of the Caspian show more affinity to *Phoca vitulina*, a northern form, than to *P. foetida* of the Mediterranean: it is therefore inferred that a strait once existed connecting this region with the Arctic Ocean. It is not clear whether the difference of level of the two chief remaining bodies of water is due to differential movement or to the settling down of the water into original inequalities in the bed. It is at any rate clear that the separation from the Arctic Ocean was due to an uplift on a large scale. The origin of the Dead Sea and of the great African lakes of the Rift valley is dealt with in the chapter on Earth Movements (see p. 201). The physical history of the great lakes of the St. Lawrence region in North America has been discussed by many geologists and geographers. During the Pleistocene Ice Age the area was occupied by an ice-sheet and the drainage from the front flowed to the Mississippi basin. The Great Lakes in something like their present form developed during the retreat of the ice, but it appears certain that they have been modified by later earth-movements, which are still going on. Around some of the lakes are old shore-lines at higher levels, which at first were necessarily horizontal, but now they are no longer so. In places they even pass down below present water-level. This implies that the earth's crust has been bent, or *warped*, as it is called in America. Such differential movement has, of course, modified the form and depths of the lakes. If the outlet were tilted upwards the lake would become larger and might even establish a new outlet at some other point, while a tilt in a different direction might drain all the water off. In any case, the shore-lines would be shifted, but obviously only the beaches that had been

raised would be visible. The present rate of southward tilting has been accurately measured and is found to be 6 inches per hundred miles per century. It is calculated that if this continues for only 1,600 years the drainage of most of the Great Lakes will be diverted past Chicago into the Mississippi. This seems an alarming prospect if we consider recent floods in that river.[1]

At one time there existed great lakes in the Great Basin region of North America. At the time of their maximum extension the climate was much moister than at present; conditions of aridity set in later, and still prevail. The shrunken relic of one of these bodies of water is the Great Salt Lake of Utah. The origin of these lakes is attributed by Russell [2] to the sinking and tilting of faulted blocks, i.e. basin-range structure (see p. 200). Lake Bonneville was about 300 miles long, and covered about 20,000 square miles, and Lake Lahontan was nearly as large. Some of the phenomena displayed by the ancient beach-terraces of these lakes are described in a subsequent section.

Crater-lakes.—It is not unusual to find the craters of dormant or extinct volcanoes occupied by lakes, which naturally possess a more or less circular form. One of the best examples is afforded by the Maare of the Eifel district in Western Germany. These now consist of circular pools of water surrounded by a low ring of fragmental rock, which has been ejected by the volcanic outbursts. There is no lava, and the ejecta consist chiefly of fragments of the country rock, mostly Devonian slate. Each crater is believed to represent a vent of single explosion. In Central Italy there also exist several crater-lakes, such as Bolsena, Bracciano, etc., which lie in the craters of some of the long-extinct volcanoes of that region. In the crater of the Soufrière in St. Vincent, before the eruption of 1902, there was a large pool of water containing abundance of sulphur compounds, which overflowed at an early stage of the eruption and caused a considerable amount of destruction.

It is believed that some at any rate of the curious salt pans and soda-lakes of Central and South Africa are essentially craters: these will be mentioned in the chapter on volcanoes.

Deposits formed in Lakes.—The nature of these depends to a great extent on the size of the lake. The larger sheets of fresh water, such as Lakes Superior, Michigan, etc., present characters very similar to those of the sea in many respects, and the deposits now being formed in them differ chiefly from those of marine origin in their organic contents. It so happens that most of the largest lakes of the world (Great Lakes of North America, Victoria Nyanza) are rather shallow and for this and other obvious reasons there is nothing in them like the true deep-sea deposits. Very little is known of the deposits of the

[1] Pirsson and Schuchert, *Textbook of Geology*, 3rd edition. New York and London, 1929, p. 302.

[2] *Sketch of the Geological History of Lake Lahontan*, p. 202.

deepest lakes, such as Baikal and Tanganyika. In a general way lake deposits consist of gravel, sand and mud, with in most cases a large proportion of vegetable matter. In northern latitudes boulders carried in by floating ice are common and in most regions stones dropped from the roots of trees brought down by floods; also bones of drowned animals. The lake-deposits found among the older stratified rocks are also of very similar character, and are readily identified by their fossils. When, however, we turn to salt lakes, and those possessing no outlet, we find an assemblage of characteristic deposits, such as beds of rock-salt, gypsum and other substances, which throw light on the conditions under which the lake exists. Numerous instances of this occur in both ancient and modern times, and many of these are dealt with in detail in the chapter on the sedimentary rocks. In lakes in desert regions a large amount of fine material is frequently carried in by wind, and forms deposits of marl, etc., which are frequently interstratified with beds of salt and gypsum. In this way some of the Trias marls may have originated; the lakes of Central Asia are now being filled up by blown sand.

At the mouths of rivers running into lakes conspicuous deltas are commonly formed, and in process of time the lake may become wholly filled up by this means. Not infrequently also there is a considerable accumulation of material near the outlet. In ordinary cases a lake is first converted into a swamp and then into level meadow-land. Such alluvial flats are common in many districts. In Chapter V instances have been given of the division of a long lake into two shorter ones by delta formation at the sides.

It is to be noted that the silting-up of lakes is in nearly all cases largely assisted by the growth of plants—peat at high elevations; rushes, sedges, etc., at lower levels. These act partly by straining off the suspended sediment, thus causing it to settle down, and partly by their own growth and decay, which give rise to an accumulation of solid matter.

Topographic Forms of Lake-shores.—In large lakes the forms of the shore-lines present a great similarity to those of the sea, with certain differences. In the first place there are no tides, hence the beach tends to be much narrower and more sharply cut, since wave-action is limited to a very narrow zone. Again, the absence of appreciable currents causes less drift of material. In some lakes there occur slight periodic oscillations of level, called *seiches*. The origin of these is not thoroughly understood, and as they usually amount to a few inches at most, their geological effects are negligible. The formation of lake-beaches must be due almost entirely to wave-action during storms.

Since the outlines of lakes are frequently very irregular, consisting of an alternation of points and bays, the accumulations of shingle, etc., forming the beach usually show a catenary curve, and this is often

marked. Sometimes what was once a small island, is connected to the shore by a double curve of beach, one on either side; this structure is called a *tombolo*. A good example is to be seen on the S.W. side of Crummock Water, in the Lake District.

Vanished Lakes.—The existence of lakes which have now disappeared is attested in various ways. Besides the alluvial flats before described, beaches at various levels may sometimes be seen. The best example in this country is afforded by the Parallel Roads of Glenroy. These are due to a glacier lake (see p. 116). In the Great Basin region of Western America high-level lake-beaches exist on a very large scale, and the best example is in the district around the Great Salt Lake of

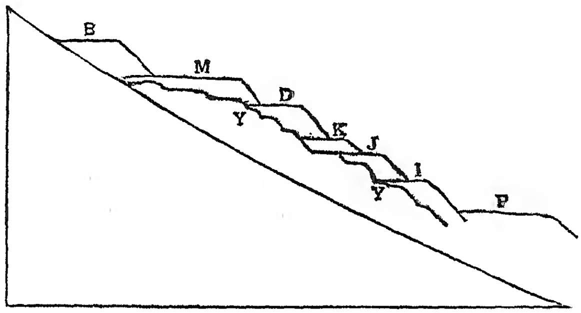


FIG. 53.—DIAGRAM TO SHOW THE BEACHES OF THE BONNEVILLE BASIN. (After Gilbert.)

Y Y, Oldest beaches; *I* to *M*, Intermediate shore-lines; *B*, Bonneville shore-line; *P*, Provo beach.

The order of succession of the oldest series, *Y Y*, has not been determined. After the formation of the last of these, the lake is supposed to have dried up. Subsequently increase of rainfall gave rise to another lake, which formed the beaches *I* to *B*, in upward succession. After the formation of *B*, the level fell rapidly to *P*. The water remained some time at this level, forming a conspicuous beach. After this the fall seems to have been continuous, so that no further terraces were formed.

Utah. This is a shrunken remnant of a once much larger sheet of water, and has now become intensely salt, owing to the loss of its outlet. Around it, at heights up to 1,000 feet above its present level, are conspicuous terraces, marking the shore-lines of the former Lake Bonneville at different periods of its existence, when the climate was much moister than it is now, probably during the Glacial period or periods (see Fig. 53).

It has been shown by Gilbert[1] that the geological history of Lake Bonneville was complex, and two distinct periods of high-water can be distinguished, separated by an interval in which the lake seems to have dried up completely. Two principal beaches can be distinguished: the Bonneville beach, about 1,000 feet above the present level

[1] *Contributions to the History of Lake Bonneville.*

of the Great Salt Lake, and the Provo beach, some 400 feet lower; between these are a series of terraces of less importance. It is possible to determine the relative ages of these beaches (see Fig. 53), and it appears that most of them were formed while the lake was rising, as shown by their mutual relations. The Bonneville beach marks the maximum height of the water, and from this point the level fell rapidly some 400 feet, owing to the wearing away of the outlet. When the level of the Provo beach had been reached, the outlet was barred by an unusually resistant bed of limestone, so that the water remained constant at this height for some time: hence an unusually conspicuous beach was formed. It is possible that at this period the lake permanently lost its outlet, owing to increase of evaporation. The terraces just described rest on an older series, but it has not been found possible to make out the order of superposition of these, and it is not known whether they were formed during a rise or fall of the water. The highest of them marks a maximum only slightly below that of the Bonneville beach, and indicates the climax of the first wet period: the Bonneville beach marks the climax of the second. Thus a study of these ancient terraces yields some important and interesting information as to climatic vicissitudes in this part of the world, while in Norway and Sweden the relation of lake-terraces to moraines and other glacial phenomena has thrown much light on the later history of the Glacial period, during the final retreat of the ice.

CHAPTER VIII

MARINE DENUDATION AND DEPOSITION

Energy of Ocean Waters.—In the introductory chapter it was pointed out that the waters of the ocean are in a constant state of movement, and that the movements are due to various causes. The most important of these are the rotation of the earth, the tides, winds, variations of temperature and pressure, and different degrees of salinity in the water itself. All these factors interact in a complex manner, into which we cannot here enter in detail. It must suffice to say that the final resultants of all these forces manifest themselves under three chief forms, which can for our present purpose be summarised as waves, currents and tides. The origin of tides is well known to be due to the rotation of the earth and the differential attractions of the sun and moon; waves are almost entirely due to wind: earthquake waves, though rare, produce enormous changes when they do occur; while the origin of currents is usually more complex, since they are due in part to tides, in part to winds, and in part to variations of temperature and salinity. All these causes together result in a continual and ever-varying circulation of the surface waters of the globe, in their efforts to attain to an equilibrium which is never reached.

It is obvious that this great moving mass of water must possess dynamical energy capable of doing work, and part of this work takes the form of destructive and constructive processes along the zone of contact between the land and the sea, and on the bed of the sea itself. It has been pointed out by Gilbert that the forms of the land are due chiefly to denudation and the forms of the sea-bottom to deposition, while the forms of shore-lines are a combination of the two, but possessing special characters of their own, since they are very largely due to the action of water-waves, complicated on ocean shores by the tides.

In marine denudation it may be doubted whether it is possible to distinguish the three processes of weathering, transport and corrasion, as in denudation of the land. It is difficult to point to anything definite in the way of weathering, except a certain amount of solution, chiefly in calcareous rocks: in point of fact, rocks kept constantly wet by sea-water are generally remarkably fresh. Any really weathered material found on a beach has usually fallen from the cliffs above, if such exist, and this is soon broken up and removed by the waves. In the same way any weathering products formed on rocks within their reach would

quickly disappear. Marine denudation is for the most part an intimate mixture of mechanical corrasion and transport, while a very important part of it consists merely in the removal of material which is hardly coherent at all. Simple transport can remove an uplifted mass of soft deposits, such as form some coasts: it is important to remember that not all land consists of hard rocks.

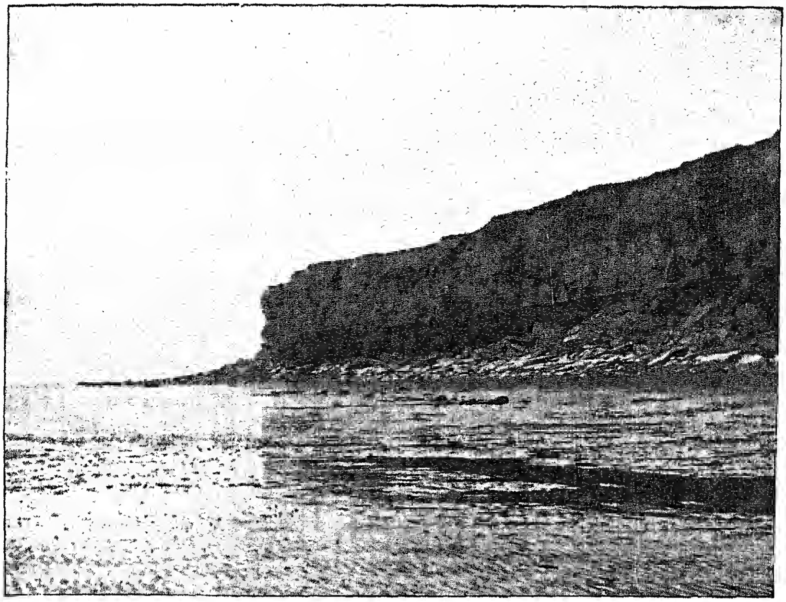
Wave-action.—Without entering into a discussion of the mechanics of wave-motion, we may say that the direct sphere of action of waves is limited below by the level of the trough of the wave and above by the level of the crest. Owing to the dash of water thrown up by the wave, the effect really extends higher than this in a diminished degree. Owing to undermining and so on, the indirect effect of waves may extend upwards to an unlimited height.

The impact of waves of pure water, free from sediment, upon hard homogeneous rock would probably produce little or no effect, although if the rock was soft or well-jointed its effect might be great. However, just as in the case of the running water of the land, the tools of wave erosion are the rock-fragments transported by the waves, and these at the same time themselves undergo comminution.

The actual mechanical power of sea-waves is enormous; the average pressure of the Atlantic waves on the western coasts of Britain is estimated at 600 lb. to the square foot in summer and 2,000 lb. in winter, while in a storm the wave-pressure of the North Sea at Dunbar was found to be 3½ tons per square foot. Besides the direct pressure or force of the blow delivered, waves also act indirectly in other ways. When a wave surges up the face of a cliff and forces its way into the cavities and along the joint-planes of the rock, the air within these cavities is suddenly and forcibly compressed, so that the effect of the blow is felt far beyond the region actually reached by the water. For this reason the forms assumed by cliffs of hard rock under the influence of wave-action depend primarily on the nature and direction of the joints. In soft or unjointed homogeneous rocks the forms assumed are less definite, depending on the character of the rock.

Forms of Shore-lines.—From these considerations it is evident that the form of a shore-line is controlled very largely by the nature of the rocks; that is to say, the Law of Structures holds good here also, with limitations. But this is not the sole factor concerned. It is well known that while the majority of coasts are undergoing destruction, in some cases the opposite process is taking place, and the land is actually gaining on the sea. This is always due to certain special conditions, which will be considered in due course. It may be pointed out here, however, that this state of affairs appears to be usually temporary, and apart from actual elevation, the ultimate fate of land masses is destruction.

The destructive action of the sea is seen to its fullest extent along



R. H. Rastall, photo.

(I) CLIFF AND BEACH AT HUNSTANTON, NORFOLK. LOWER GREENSAND, HUNSTANTON RED ROCK AND CHALK.

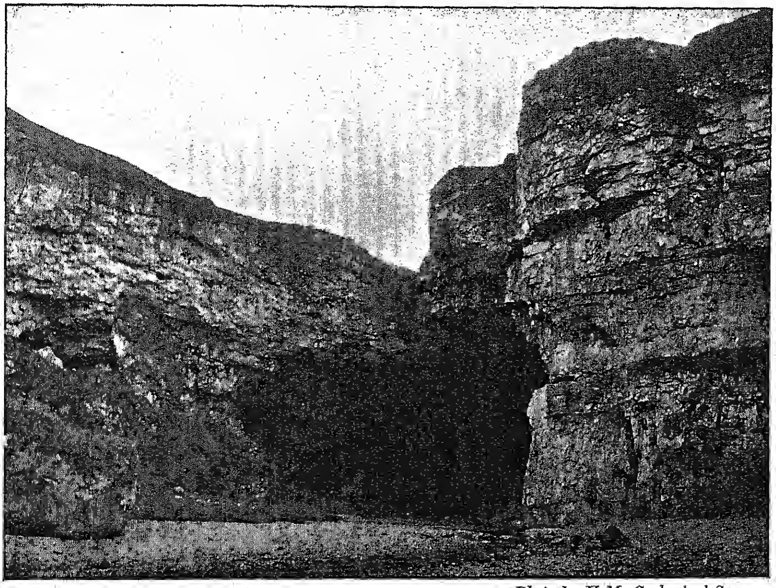


Photo by H.M. Geological Survey.

(II) CLIFFS OF CAMBRIAN DOLOMITE WITH CAVE DUE TO MARINE EROSION SMOO CAVE, DURNESS, SUTHERLAND.

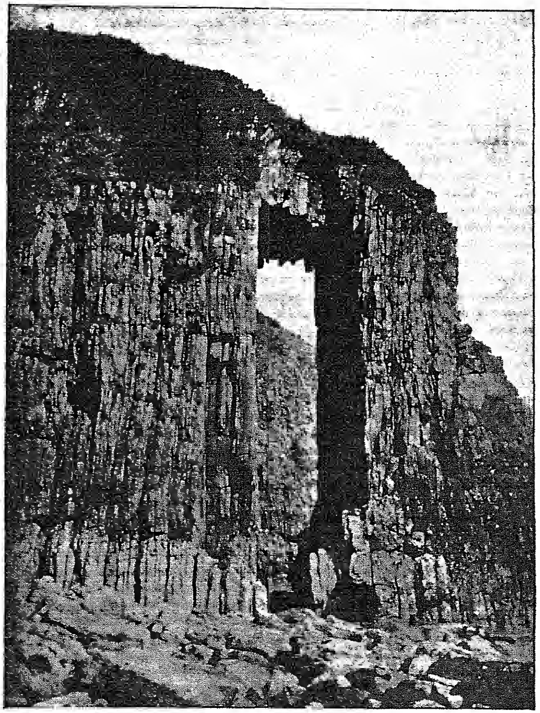
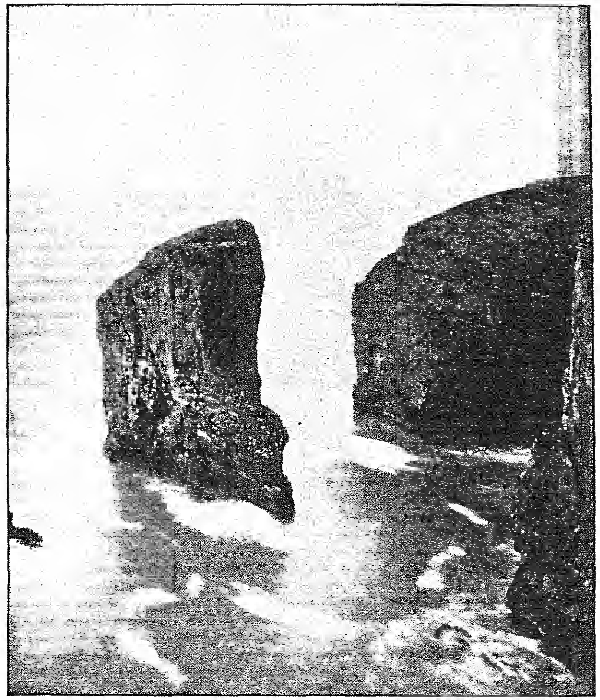


Photo by H.M. Geological Survey.

(I) NATURAL ARCH IN CARBONIFEROUS LIMESTONE, MANORBIER, PEMBROKE.



(II) STACKS ON THE COAST OF PEMBROKESHIRE.

those coast-lines where the subaqueous slope is abrupt, with deep water close to land, since here the waves can exert their fullest power: where the slope is very gradual, the waves break far from land and have lost much of their energy through friction before they reach the shore. In such areas deposition often occurs off shore to such an extent as to build up bars, sandbanks, shoals and other accumulations either just above or just below the surface.

In the study of the topographic forms of existing shore-lines, a special difficulty arises from the fact that it is not always easy to decide whether the features seen are actually due to wave and current denudation at and near sea-level, or to the submergence of structures formed as the result of denudation of a land-surface. In many cases it is quite certain that the peculiar features of certain shore-lines are due to this latter cause. As examples, mention may be made of the long inlets of south-western England, such as Plymouth and Falmouth harbours and similar instances in Brittany and north-western Spain. Here the steep slopes down to and below water-level and the general absence of beaches clearly indicate drowning of normal river valleys. (For a further description see p. 145.)

Cliffs.—It is only under exceptional circumstances that the land surface passes down below sea-level in an unbroken regular slope. The coast-line is nearly always marked by a more or less abrupt slope, which is commonly spoken of as a cliff (Figs. 54 and 55). The formation of a cliff (Plate XIX) is not a simple process, but is the resultant of several causes. In the first place, we have the action of the waves acting at the base only, thus tending to undermine the land; and, second, there are the ordinary subaerial agents of denudation acting on all points of the cliff, and tending to wear away the upper parts faster than the lower, and thus reducing the steepness of the slope. The ultimate form of the cliff thus depends on three principal factors: the structure and nature of the rock, the rate of marine denudation, and the rate of subaerial denudation. Since all these factors may vary indefinitely, a great diversity of forms may be produced. Some of the conditions specially favouring the formation of steep cliffs are,—rapid marine erosion acting on hard rocks which are but little affected by the weather: in this case the resulting forms depend primarily on the disposition of the joints, as is shown in Fig. 54; secondly, steep or even overhanging cliffs are often produced when soft rocks are overlain by a harder layer, as is well seen in many parts of the north-east coast of Yorkshire, where cliffs of soft shale are capped by thick beds of hard and well-jointed sandstone. Even such an apparently soft rock as the Chalk often forms steep cliffs, where it is rapidly undercut at the base by wave-action; good examples of such cliffs are seen at Dover, Beachy Head and Flamborough Head. A special feature of Chalk cliffs is their readiness to form caves and isolated pinnacles, such as the Needles at the

western extremity of the Isle of Wight, and the King and Queen rocks at Flamborough Head. In this case wave-action is possibly assisted to some extent by solution.

However, the formation of isolated pinnacles of rock is not by any means confined to Chalk. Innumerable examples exist around the British and other coasts, in rocks of every kind. A well-known example on a very large scale is the Old Man of Hoy, in the Orkneys, so graphically described by Sir Archibald Geikie.[1] The *stacks* on the coast of Pembroke (Plate XX (ii)), and those near Duncansby Head in Caithness, may also be mentioned.

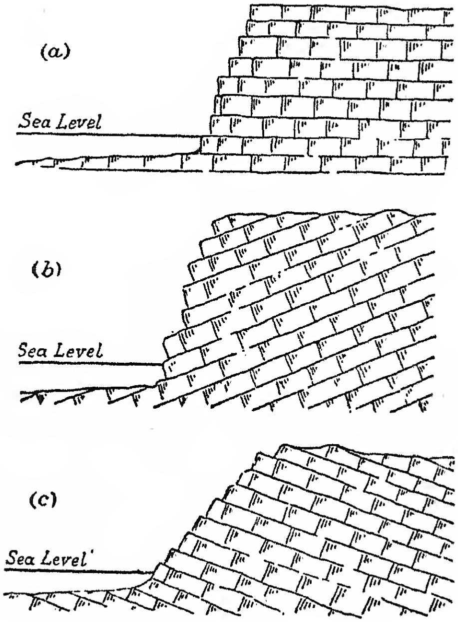


FIG. 54.
Well-jointed rock with bedding-planes. (*a*) Horizontal; (*b*) dipping towards the sea; (*c*) dipping away from the sea.

Where a cliff composed of well jointed or soluble rock, such as columnar basalt or limestone, is exposed to strong wave action caves are often formed. The process is in reality merely an exaggeration of the effect of waves on open joints as already described and scarcely needs further elaboration. One peculiar result is that sometimes the effect penetrates so far that an opening in the ground is formed some distance inland and during storms spray may be shot up through these openings, which are often very like the swallow holes in limestone regions, though formed from below instead of from above: they are

[1] *Geological Sketches at Home and Abroad*, p. 26.

called *blow-holes*. In many places round the British coasts there are 'natural arches' directly due to wave-erosion. Very steep or vertical jointing is favourable to their formation. A fine example at Torquay has been often figured.

When marine erosion acts on unjointed rocks somewhat different effects are produced, and these are specially notable in regions where there is little or no tide. A good example has been described by Günther[1] in the island of Capri, which consists for the greater part of fairly homogeneous limestone. Here the most conspicuous feature is the formation of a deep groove at mean tide-level, and the cliffs above it frequently overhang. In Capri similar grooves occur at different heights above present sea-level, indicating recent uplift and tilting of the land, since the height of the most conspicuous groove varies from 23 feet at one end of the island to 12 feet at the other. This movement has occurred since the first century A.D. The raised cliffs and terraces of Christmas Island,[2] which are cut out of reef-limestones of various ages, also overhang very markedly as a result of wave-action. In fact, undercutting of this kind is one of the most conspicuous features to be seen in the raised coral reefs of the Pacific (see Plate XXII).

Comminution of Material.—We must next consider the effect of wave and current action on the material itself. The primary source of beach-material is to be sought in the fragments detached from the cliffs and shore-platform by the force of the waves, and its character naturally varies according to the kind of rock acted on. These fragments are constantly rolled hither and thither, so that they gradually become less and less in size and much rounded and smoothed. This smoothness is highly characteristic of beach-material, and it is also clearly to be seen in rock-surfaces still in situ over which wave-action has full play, so that rocks on the shore are for the most part exceedingly slippery, and this slipperiness is often accentuated by a coating of sea-weed. The larger blocks and shingle of the beach, by a constant movement to and fro, become smaller and smaller, so that they are eventually ground down to sand. The shape of sand-grains depends on the conditions of formation, but the sand of sea-beaches is as a rule moderately rounded, less so than in the case of desert sands. Occasionally, however, where sand has remained for a long time in an eddy, the grains become very rounded. The mineral constitution of sands is fully treated in Chapter IX.

Wave-cut Platforms.—Where a shore-line composed of hard rocks is undergoing denudation by wave action there often extends from the foot of the cliff a platform having a very gentle slope seawards. The upper part, lying between tide-marks in some cases remains as bare

[1] *Geog. Journ.*, August 1903, p. 121.
[2] C. W. Andrews, *Monograph of Christmas Island*, p. 6, etc.; *Geog. Journ.*, vol. xiii., 1899, p. 17.

rock, while in other instances it is covered by beach material: the difference depends on the hardness and consequent rate of denudation of the rock. An instructive example is to be seen at Whitby, Yorkshire, where a large fault runs along the west side of the harbour. On the east the cliffs of Lias capped by sandstone are high and very steep, and from their foot (high-water mark) extends a platform of bare rock with a very gentle slope far beyond low-water mark. On the west side of the harbour the much lower cliffs are of soft sandstone and boulder clay, and the beach consists of sand and shingle. This means that the rock-platform here, which certainly exists, being composed of softer material, has been denuded more deeply by the waves and therefore beach material can remain on it, which is not possible on the bare rock at a higher level on the east side. This type of bare rock-platform, locally called 'The Scar,' [1] is characteristic of nearly the whole stretch of coast from Ravenscar (Peak) to Saltburn, about 30 miles. Under

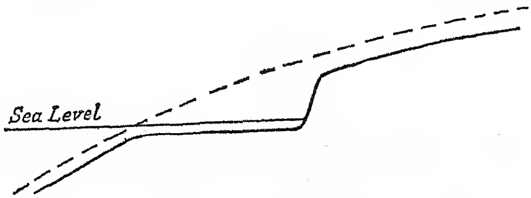


FIG. 55.

The dotted line represents the original form of the uplifted land; the continuous line shows the wave-platform and cliff after denudation has been proceeding for some time.

favourable conditions of tide and beach a curious platform of Chalk is to be seen at Cromer. Obviously it is usually impossible to determine how far such platforms really extend under water, and many are no doubt permanently invisible, owing to their covering of loose material. In places where the rock thus undergoing erosion varies much in hardness masses projecting from the platform to different heights form the reefs, skerries, stacks and islands so common and characteristic of rock-bound coasts, for example the Scandinavian skjaergaard or skärgård.

Transport of Material.—We have seen in the preceding sections that waves are the chief agents in the denudation of shore-lines, and in the comminution of the material thus set free. It now remains to consider what happens to this material. It is well known to everybody who has been to the seaside that beach pebbles are constantly being rolled about by the waves, and it may be noticed what surprisingly large pebbles, especially if well rounded, can be moved by quite gentle wave

[1] This word is related to the Norse skjaer, and also probably to skerry. Inland the same word means a crag or cliff, usually an escarpment: e.g. Roulston Scar, near Thirsk, overlooking the Vale of York.

action. This is due to the fact that the effective density of a pebble in water is less than the specific gravity in air by the weight of the water displaced. Hence the effective density of a quartz pebble is (2·65 — 1), a reduction of more than one-third. With flint the effect is still more marked, but with heavier rocks it is less. This greatly facilitates the sorting effect so common in moving water, and utilised in the operation of panning for heavy minerals. When this fact is borne in mind it will be seen that the stories of blocks of rock of gigantic weight thrown up by the waves are really 30 or 40 per cent. less astonishing than they are generally supposed to be, though often sufficiently remarkable even with this qualification.

It is a special peculiarity of wave-action on a normal gently sloping shore, that for waves of a given magnitude there is a certain critical size of material—shingle or sand as the case may be. All fragments above this critical size tend to be moved towards the land and piled up on its margin, whereas fragments below this limiting size travel away from the land, towards deeper water. This curious phenomenon results from the oscillatory nature of wave-motion, with an alternation of rapid forward motion and slower backwash. The coarser material is therefore deposited on the shore, usually near high-water mark; below this the material gradually becomes finer and finer towards the sea, while the finest of all is carried below the limits of wave action and forms the deep water marine deposits, which will be described in detail in due course.

Beaches and other Accumulations of the Shore-line.—The material thus cast upon the margin of the land by wave-action, constitutes what is commonly known as the beach (Fig. 56). Beaches consist of rock-fragments, and are popularly spoken of as sand, shingle, etc., according

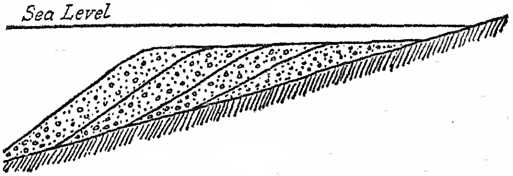


Fig. 56.—Formation of Beach Deposits.

to the size of the fragments, which varies according to the different conditions. The form and character of the beach as a whole also vary according to the strength of the waves and currents, etc., and the nature of the materials. In a region of hard rocks exposed to strong wave and current action there is often little or no beach, and on coast-lines of strong relief beaches are commonly developed in the indentations only. On the other hand, gently sloping shores of soft rock are often bordered by great accumulations of beach-material. As a rule, beaches show

the highest development where the submarine slope is very gentle, but they depend so much on individual conditions that it is difficult to lay down any general laws.

Thus the general effect of wave-action is to pile up the shingle of the beach at or near the line where the waves break. It appears that the maximum deposit takes place below the line of maximum agitation of the water. On steep shores this is close to the land, often actually at the foot of the cliffs. But on a gently sloping shore the waves often break far out, so that the maximum deposit takes place some distance from land. This may eventually result in the formation of an off-shore barrier, with a lagoon behind it, as is seen on many low coast-lines. Similar barriers are often formed across small bays, but here another factor comes into play also: transport of material along the shore, and this must now be considered.

Transport along Shore-lines.—At first sight it seems plausible to attribute the transport of material along shore-lines to tides and currents, but in spite of many positive statements to that effect it may be doubted whether they really play much part in along-shore drift, though currents certainly do transport finely divided material in suspension and floating organisms in deeper water at some distance from the land. A current alone without the assistance of waves, unless incredibly rapid, could not transport pebbles of any considerable size, though a strong tidal scour in a narrow channel might do so. The most important factor in reality seems to be the oblique impact of waves on a sloping beach. In most places there is a prevailing or at least a most effective wind: in the English Channel from the S.W., in the North Sea from the N.E. The most important part of the process is as follows: when a powerful wave strikes a beach the upward travel of the pebbles and sand is in the same direction as the wave; in the case supposed, obliquely, but with the weaker back-wash they roll straight down the steepest slope. With the next wave they go up again obliquely and so on. Hence any individual pebble travels in a series of zig-zags, obliquely up and straight down.[1] The generalised direction of travel of a pebble is therefore along the beach, without the intervention of any tide or current. The origin of Dungeness, one of the largest accumulations of shingle in this country, is thus explained by W. V. Lewis,[2] who believes that tidal currents have here had little effect compared to waves, contrary to the opinion generally held in this particular case.

It is well known that there is a general eastward movement of shingle in the English Channel, and at many of the south-coast seaside towns elaborate systems of groynes and other constructions have been

[1] The zig-zags are not really quite sharp, but somewhat rounded off, both at the top and the bottom.

[2] W. V. Lewis, *Geog. Journ.*, 80, 1932 309.

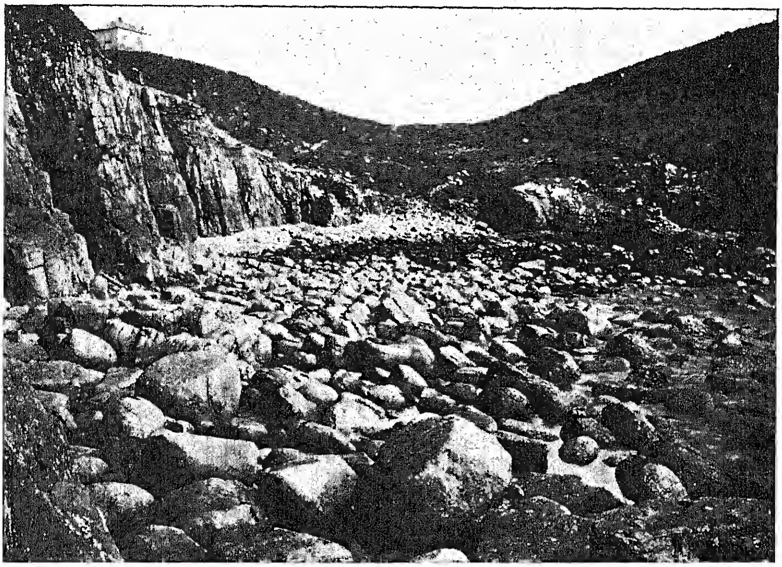


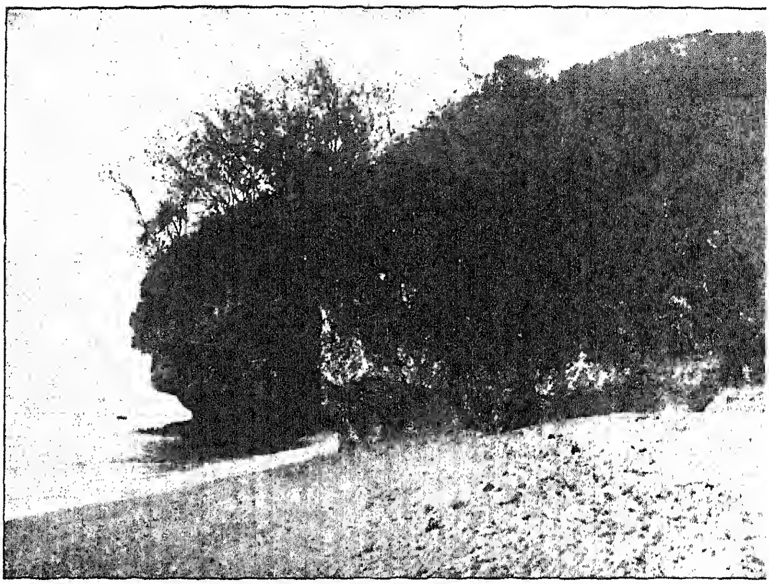
Photo by H.M. Geological Survey.

(I) PEBBLE BEACH, SENNEN, CORNWALL.

Photo by H.M. Geological Survey.

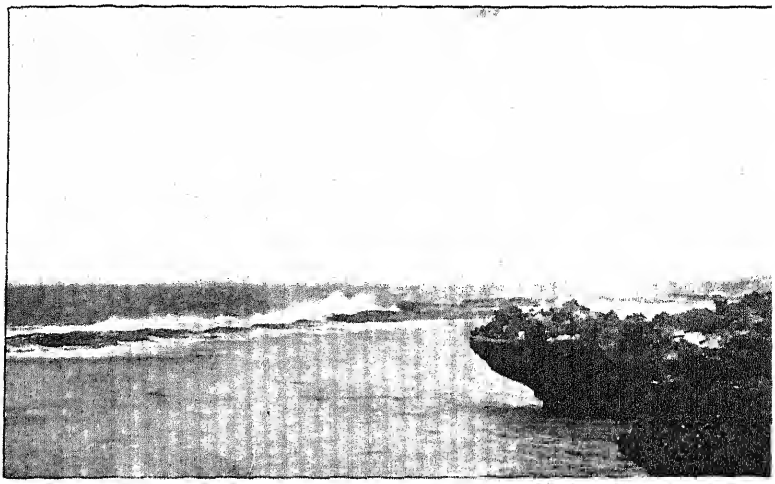
(II) CLIFFS DETERMINED BY JOINTING IN GRANITE, LAND'S END, CORNWALL.

PLATE XXII



J. J. Lister, photo.

(I) RAISED CORAL REEF FORMING UNDER-CUT CLIFF: WEST SIDE OF EUA, TONGA ISLANDS.



J. J. Lister, photo

(II) CORAL REEFS AT DIFFERENT LEVELS: RAISED REEF IN THE FOREGROUND, MODERN REEF IN THE DISTANCE. SOUTH OF TONGATABU, TONGA ISLANDS.

devised in an attempt to arrest it, generally with very unpicturesque results.

One of the most important accumulations of shingle in this country is the well-known Chesil Beach [1] which borders the coast for many miles west of Portland. Behind the shingle beach is a long narrow lagoon, known as the Fleet. The chief difficulty with regard to the source of the material of this beach lies in the fact that the pebbles are large at

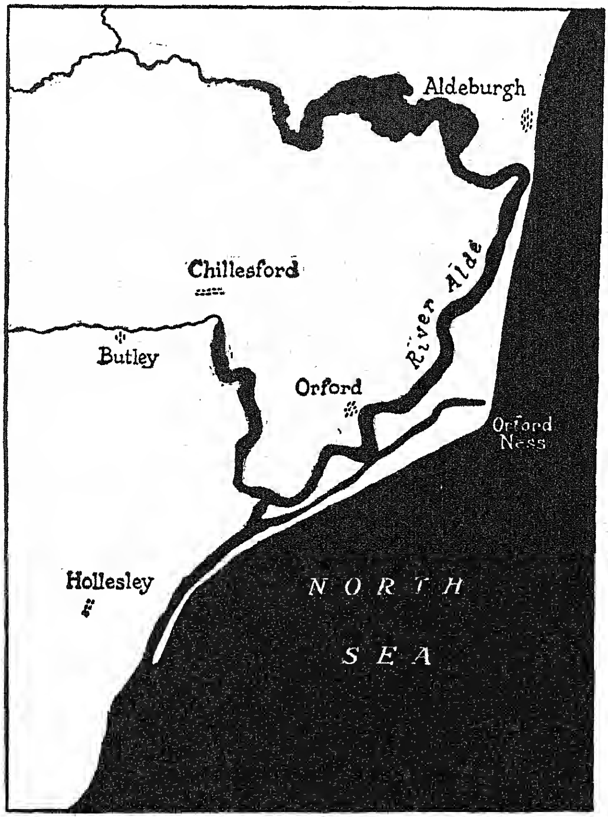


Fig. 57.—The River Alde, Suffolk.
Scale, 1 inch to 3 miles.

the eastern end and smaller towards the west; this is the opposite of what would be expected from a general easterly drift in the Channel. It appears, however, that material is really supplied to the beach from both ends, and not from the eastern end only, as formerly supposed, and the material fed in at the western end is mostly fine, the coarse

[1] Vaughan Cornish, *Geog. Journ.*, xi., 1898, 628. Baden-Powell, *Geol. Mag.*, lxvii., 1930, 499.

material from the west being stopped by small promontories. The material supplied from the east, on the other hand, is mostly coarse, and at the present time a large proportion of it consists of rubbish tipped from the Portland quarries; at this end there is a strong outward current which carries off much fine material, and so increases the proportion of large fragments.

Other interesting cases of peculiarities of topography due to longshore drift are found on the east coast of England, especially in Norfolk and Suffolk. The most effective storm-wind in the North Sea blows from the N.E., and the set of the tides is southwards. Consequently, when the waves are most powerful they impinge obliquely on the coast and cause a pronounced southerly drift of shingle and sand. The effect of this is well seen in the course of the river Alde, which approaches within less than a hundred yards of the sea at Aldeburgh and then turns abruptly somewhat west of south and flows for ten miles parallel to the coast inside a great bank of shingle (see map, Fig. 57.)[1] A similar phenomenon is seen at the combined mouth of the rivers Bure, Yare and Waveney at Yarmouth: a great part of this town stands on the shingle bank thus formed. It has already been pointed out in the chapter on Lakes that the Norfolk Broads are due to the blocking of river mouths in the same way.

Sand and Shingle Spits.—When material thus drifting along a smooth shore reaches the mouth of a bay or estuary it can no longer be carried forward, owing to the absence of disturbance in the more sheltered and

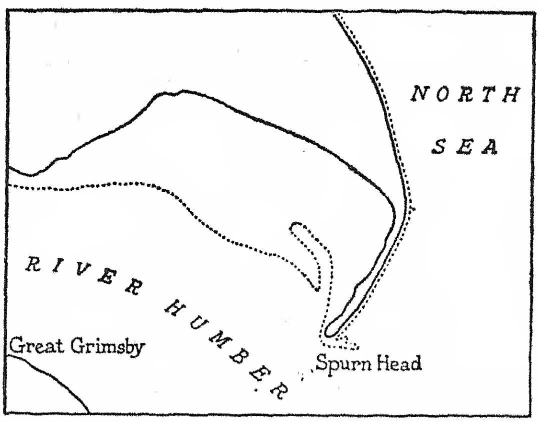


FIG. 58.—SPURN HEAD, AT THE MOUTH OF THE HUMBER.
The dotted line is low-water mark.

deeper water. It will therefore in course of time build up a ridge of shingle or sand which may extend completely across the opening.

[1] Steers, *Proc. Geol. Ass.*, xxxvii., 1926, 306.

More commonly, however, the scour of the tides and of rivers keeps a channel open, generally at or near the further side towards which the current is travelling, and the result is a *spit*. The manner of formation of a spit is essentially like that of a railway embankment, in which the material is carried along the top and tipped over the end, thus continually lengthening the embankment. An excellent example of this kind is to be seen in the long spit of sand and shingle stretching out from Spurn Point partly across the channel of the Humber (Fig. 58), and this shows very well the recurved form which is so characteristic, and is due to the combined action of waves and currents, both inward and outward, but dominantly from the north.

The Morphology and Nomenclature of Shore-lines. Perfect precision in the use of descriptive terms is not easy to attain, and this is certainly true of the subject of this chapter. The words *coast* and *shore* are often used as if they were interchangeable, but it would seem desirable to restrict the meaning of coast to the broadest features, thus: the east coast of England; a fjord coast; where the idea is not confined to the actual line of contact of land and sea. On the other hand it is suitable to speak of the shore of a lake, a winding shore-line and so on. To most people *beach* conveys the idea of the space between tide-marks, together with that, if any, up to the foot of a cliff. On low shores a storm-beach or sandhills, or both, are often conspicuous: a storm-beach is of course not covered by the sea at ordinary high tides, but only exceptionally the waves reach it.[1] Logically a bare rock platform should also be called a beach, though generally it is not. In England the term *foreshore* has a definite legal meaning: namely, the area between tide-marks, even extending up tidal rivers.

In nearly all cases, however far they extend under water, the beach or rock platform and their continuation end in a more or less definite and considerably steeper slope, where a change takes place in the character of the deposits. This is called the *continental slope* and marks the edge of the *continental platform*. This will be discussed in a later section. Finally we pass down to the *ocean floor*.

The foregoing are some of the more important features of a shore-line as seen in section: we must now turn to a brief consideration of shore-lines in plan, although this is geography rather than geology.

Types of Coast Lines.—Many attempts have been made to draw up a classification of coasts; some morphological, depending on form and structure; and some genetic, founded on origin, but none can be regarded as satisfactory, as the variety of types to be included is so great and transition forms so numerous. One very important factor to be considered is that the form of a coast-line may be modified in two independent ways. Land may be lost either by actual erosion, or by

[1] Great masses of shingle above high-water mark, like those of Dungeness, are really exaggerated storm beaches.

submergence without change of form, and similarly land gains on the sea either by uplift or by the building up of new deposits. Hence coast-lines can be classified as *coasts of emergence* and *coasts of submergence*, without taking into account how the processes have been brought about. This has the advantage of avoiding the difficult question of whether in a given case it is the level of the land or of the sea that has changed, or neither.

Our own country affords excellent examples of two markedly different types of coast. Every one has heard of the rapid loss of land in East Anglia and Yorkshire, where historic towns have disappeared, but it is probably less well known how much new land has been formed in the west. In the early years of the present century the whole subject was investigated by a Royal Commission, who reported in 1911, as one of the results of their work, that in a period of about 35 years the British Isles (including Ireland) had lost about 6,600 acres (slightly more than 10 square miles) and gained about 48,000 acres, but it has to be remembered that the land lost is nearly all of much greater value than the land gained, the latter being mainly sand-hills and mud-flats in estuaries and so on, while most of the loss is good agricultural or building land. The Commission also reported that they could find no evidence of any important change now in progress in the relative levels of land and sea.[1] Hence it is clear that in England we have examples of a coast of submergence due to denudation (East Coast) and in many places on the west a coast of emergence due to deposit, without any change of levels. It has already been mentioned that in Devon and Cornwall there is evidence of submergence by actual relative movement in times not long past, but this now seems to have stopped. In parts of the country there also exist raised beaches, which indicate an actual rise of the land or fall of the sea in geologically recent times. This matter is discussed in Chapter X.

So far as the actual forms of coast-lines are concerned, the most important factor is obviously the character of the land and consequently its geological structure. As a simple example we may compare the types of coast which (*a*) run parallel to, and (*b*) cut across a mountain chain; for example the long, straight coast-line of northern Spain, with few good harbours, in contrast to the deeply indented rias facing the Atlantic round the N.W. corner. The east coast of the Adriatic is also determined by a mountain chain, but this is partly submerged, giving rise to long inlets and narrow islands parallel to the coast. The long straight coast of Natal is certainly due to faulting, as the same flat-lying strata of the Karroo System are found both on the shore and far inland at a height of several thousand feet: probably most of the very simple outline of South Africa is due to faulting, as even where folded mountain chains run out to sea in the S.E. corner of Cape

[1] Third Report, Royal Commission on Coast Erosion, 1911, p. 35. [Cd. 5708.]

Colony there are no notable indentations. It is generally considered also that the long, smooth west coast of Italy is due to the collapse of a more or less circular block to form the Tyrrhenian Sea. With this may be compared the jagged outline of Greece, carved out of several N.–S. folded chains.

Fjords, Fjards and Rias.—Perhaps the most striking of all types is that usually called a fjord coast, which affords some of the most spectacular scenery of the world. A brief reference has already been made to fjords in the chapter on glaciation, and it is now necessary to amplify this. By far the greater number of fjords are in glaciated areas: Norway, Scotland, Greenland, British Columbia, New Zealand. It is very doubtful whether the long narrow channels of the Dalmatian coast, often quoted as examples of fjords in an unglaciated area, should bear that name. They are the valleys of a partly drowned mountain chain, parallel to the coast, and nearly all of them are open to the sea at both ends, whereas the northern fjords are usually continued far inland by valleys of the same type and are more or less at right angles to the coast.

A typical fjord then is the continuation of a narrow, deep, steep-sided land-valley, generally U-shaped, or with a U within a V, with hanging tributaries, and often lakes lying in rock-basins. Below the point where salt water begins the valley is of the same type and often the depth of water is very great. Moreover, this depth varies in a particular way, deep basins alternating with shallower stretches, and there is often a conspicuously shallow portion, or bar, at or near the mouth. In the case of two Scottish lochs, Etive and Leven, as already described (p. 127), the rock bar is between tide-marks. All these features are really only consistent with glacial erosion. Some geologists, especially Gregory,[1] have opposed a glacial origin, and explained fjords as due to ordinary water denudation acting along faults and joint-fractures. In support of this the conspicuous zig-zag rectangular plan of many of the Norwegian fjords is cited, but the argument applies equally well to glacial erosion, which also would naturally avail itself of lines of weakness in the rocks. The alignment of the fjords is in many cases undoubtedly due to fracture systems, but it may be taken as now generally accepted that the actual excavation is due to glaciers.

A fjord coast is generally quoted as an example of submergence, but this seems by no means necessary. There would appear to be no reason against glacial erosion below sea-level, though it must be admitted that the depth of some of the Norwegian fjords is rather excessive on this hypothesis. Against this must be set the fact that around them raised beaches at great heights are common, showing that the

[1] Gregory, *The Nature and Origin of Fjords*, London, Murray, 1913. This is by far the best descriptive work on the subject, though the main thesis is probably erroneous.

latest movement at any rate was emergence of the land and not submergence.

In southern Sweden and in other places there are found inlets of the sea, which on a map look like fjords, but are surrounded by quite low ground: these are called *fjards*, and many of them, at any rate, have also been excavated by glaciers, as they have inner basins deeper than the bar, and are therefore not drowned river valleys.

Reference has already been made to the long deep inlets seen in non-glaciated areas like south-western England, Brittany and north-western Spain: these do not show deep inner basins, but their floors have a gradual slope from head to mouth, a continuation of the slope of the river valley that runs into them. Many of them are also much too deep to have been excavated by a river at the present level and the only possible explanation is actual submergence of the land. In Spain such inlets, which form very fine harbours, are called *Rias*, and this name is now applied to the whole class: the Ria type of coast.

It is not possible on an uncontoured map to distinguish between fjords, fjards and rias: measurements of the heights of the land and soundings are necessary.[1]

Coasts of Emergence.—One division of this class may be dismissed very briefly, namely, coasts formed by deposition without change of level. The most important of these are either (*a*) fillings of bays and estuaries, already mentioned as well developed in the west of England and Wales: the Bristol Channel; the estuary of the Dee; Morecambe Bay; the Solway: or (*b*) large-scale deltas, such as those of the Rhine, Rhone, Nile, Mississippi and a large part of China (see page 59). But coast-lines formed by actual elevation of the sea-floor need rather fuller treatment.

Long ago Gilbert pointed out that the land is, on the whole, an area of denudation and therefore of varied topography, while the sea-floor, being mainly an area of deposit, is characterised by gently inclined surfaces of little relief and smooth contours. The effect of the bodily uplift of a shore with well marked beaches or a rock platform ending in a steep slope can be easily visualised and indeed can be seen in many places in Scotland and Norway (see Chapter X, p. 204).

The best-known example of the uplift of a smooth, gently sloping sea-floor to form a considerable land area is the coastal belt of the eastern United States. This has been described by many American writers.[2] Here, especially, in North and South Carolina and Georgia,

[1] An easily accessible contoured map of a typical fjord country is Bartholomew's *Half-inch Map of Scotland*, Sheet 11, Oban District. In this the rectangular plan is very conspicuous, and the rock-basins in the lakes show up well.

[2] See especially D. W. Johnson, *Shore Processes and Shoreline Development*, New York, Wiley, and London, Chapman and Hall, 1919. This is by far the best book on the whole subject and contains very complete bibliographies up to its date. It is by no means confined to America, but deals fully with many European and other coasts.

is a wide low-lying coastal plain, consisting of geologically recent deposits: in fact an elevated sea-floor. On the landward side this ends rather abruptly at the foot of a region of moderate relief, an old coast-line, where many rivers come down somewhat steeply in rapids and falls, often valuable as sources of water-power. This is called the *Fall Line.* Still further inland are ranges of high mountains, running from N.E. to S.W., the Alleghanies. The whole thing shows up very clearly in Plate 90 of the *Times Atlas.* Owing to changes after the uplift the actual shore-line has become very complicated in detail, by formation of shingle spits, sand-bars and so on, especially in the northern part, but the general trend from Cape Hatteras to Florida is a smooth sigmoidal curve. Other examples of similar coastal plains are to be seen in Argentina, south of the Rio de la Plata and along the east coast of India. Hence it appears that the dominant characteristic of a coast-line of recent uplift is simplicity—either straightness or broad flowing curves.

Coastal Bars and Reefs.—A very common feature of low shore-lines with a gentle submarine slope is the formation of off-shore shingle bars and sand bars, often enclosing lagoons, as well as many varieties of banks and shoals, at varying heights often between tide-levels, but some above high-water mark and some permanently submerged. The subject is very complicated and the real reason for their formation does not seem to be decided. No doubt the causes differ in different instances. The whole matter is geographical rather than geological, but the type of deposit formed in lagoons and similar situations is of some importance among the older rocks. The formation of coral reefs is discussed at the end of this chapter. Reefs of hard rock other than coral clearly belong to coast lines of denudation (differential wave erosion).

Origin of Shore-line Features in General.—So far various instances have been discussed where there is no doubt as to the reason for the existence of coasts and shore-lines in their present form, but it should be made clear that it is not always easy or even possible to decide between different explanations of the same features. The older school of geologists tended to attribute everything to wave-erosion acting on rocks of differing hardness, whereas in modern times there has been an inclination to emphasise the importance of actual drowning of subaerial topography: both of these explanations apply in different cases, but each alone will not explain every case. Let us consider, for example, the long narrow bays of South-west Ireland, so often quoted as examples of the erosive power of the Atlantic waves. This explanation will not work, for the simple reason that the material excavated by the waves could not be removed after the inlet had reached a certain very limited length: it would be choked with its own débris, as soon as this could no longer escape sideways, and erosion would stop. These bays have

too great a depth of water to have been excavated by river erosion at the present land-level, and either drowning of land valleys or glacial action must be invoked. Nevertheless differential wave erosion of rocks of different hardness without change of level can give an indented shore-line, as shown in the actual example on a small scale given in Fig. 60, where also the curved form of beaches in the bays can be seen,

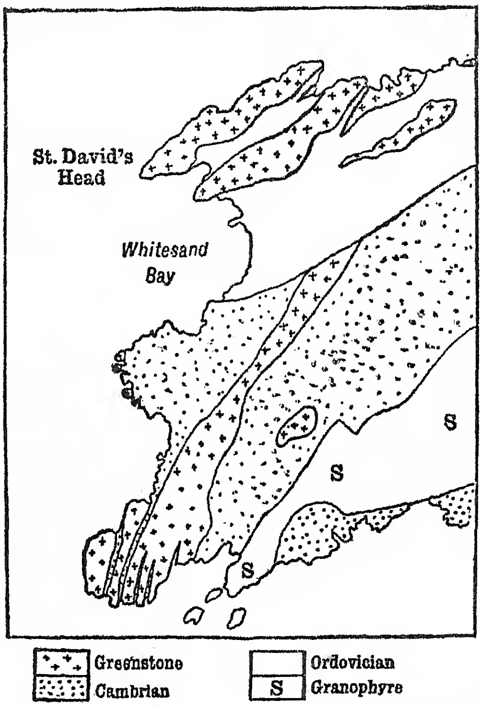


FIG. 59.—MAP OF THE COAST OF PEMBROKESHIRE, SOUTH WALES. Showing how the hardness of the rock affects the shore-line. From the map of the Geological Survey. Scale, 1 inch to 1 mile.

showing, as does also the Chesil Beach on a larger scale, that a smoothly curved shore-line does not necessarily indicate drowning or emergence.

Islands.—From the geological point of view islands can be treated very briefly and on broad lines, though they show almost infinite variety in detail. The usual classification is into two groups, continental and oceanic, and this corresponds very well with reality. The first group are those which either, (*a*) lately formed part of the near-by mainland, or (*b*) have a structure similar to continental lands, though perhaps recent separation cannot be proved. Of the first group Great Britain and Ireland afford typical examples. The structure of southern

England is a direct continuation of that of France and Belgium, and the same applies to Ireland in relation to Great Britain. It is known that in both cases separation is geologically recent. In group (*b*), among the great islands of the world, New Zealand, Madagascar and Greenland may be quoted as examples.

True oceanic islands are all either of volcanic origin, or made of coral rock, or both, and as such are treated elsewhere. Examples are the volcanic island-groups of the mid-Atlantic and the coral islands of the Pacific and Indian oceans.

Islands formed by direct accumulation of marine sediment do not amount to much: they are usually parts of deltas or estuary fillings, or unusually large coastal bars and sand-banks.

Marine Deposits.—The deposits now forming on the floor of the sea will in course of time be transformed into rocks similar to those composing the older sedimentary strata, except in so far as they are modified by such things as cinders and broken bottles thrown overboard from ships. Therefore their nature will only be discussed briefly here and from a general point of view, leaving details of mineral composition for the chapter on the sedimentary rocks. They will be described in terms of gravel, sand and so on as used in earlier sections.

It has already been explained that as a result of wave action on shore-lines there is a general tendency for coarse material to travel up the beach to the limit of wave action and for the finer particles to be sucked back seawards. Since it is known that very finely divided material is being deposited at depths far beyond the limits of wave action, tides and currents must also play a part. Hence there is a gradation in the size of the component particles of deposits from the land outwards, which may be generalised as the normal sequence: gravel, sand, silt, mud. These are the *terrigenous* deposits, derived from the land. The rest are called *pelagic*. Of great importance also are the organic deposits: shells, corals, etc., dead or alive. These may accompany or replace the others within a wide range of depth. Since many organisms, both animal and vegetable, live floating or swimming in the sea their remains may be found on its floor far beyond the range of the terrigenous sediments.

We may thus regard the land areas as surrounded by a series of deposits of progressively decreasing grain size. Their boundaries are not sharp, except the landward limit; nevertheless it is possible to demarcate them in general terms. The typical succession was first clearly established as one of the results of the voyage of H.M.S. *Challenger* in the early seventies of the last century, and the nomenclature then suggested has been almost universally adopted.[1] The classification here given is adapted and simplified from this, with a slightly

[1] Murray and Renard: *Report on the Scientific Results of the Voyage of H.M.S. Challenger; Deep Sea Deposits.* London, 1891.

different terminology, partly due to the late Professor Marr.[1] but the basis is the same: the principle of decrease of grain size away from the land.

Belts of Deposition.—Each of the zones of deposit may be conveniently called a belt, since they surround the land more or less parallel to the coast. The shore deposits naturally must follow the windings of the shore-line, and the others, while varying much in width in different places, still maintain a general parallelism. The shallow water belt, next below low-water mark, shows the greatest amount of variation in accordance with local conditions, and it is therefore here called the *Belt of Variables*, as suggested by Marr.[2]

	Cobbles and Boulders	Storm Beach
High Water Mark		
	Gravels, Sands, Shell Banks	Shore Belt
Low Water Mark		
	Sands, Silts, Calcareous Deposits	Belt of Variables
Inner Mud Line		
	Muds	Mud Belt
Outer Mud Line		
	Oozes and Red Clay	Ocean Floor

The width of these belts varies greatly: the storm beach is often only a few yards; the next belts, though shown as equal in the table are in reality when expressed in miles more nearly in the ratio of 1 : 10 : 100, each probably multiplied or divided by a small factor.[3] It is rarely that a true beach is more than a mile wide, and usually much less. This belt also includes rock platforms left dry at low tide, which are often bare of sediment or with only a little sand and gravel in hollows: broken shells are often very abundant, or living limpets, etc. attached to the rock. In places, opposite the mouths of large rivers and especially in estuaries, the mud belt may encroach on the belt of variables, and even extend up to high water mark.

Most of the terms used in this table explain themselves, but a few words are necessary as to one or two of them. There has long been a need for a name for rounded blocks larger than gravel, but not so large as what is commonly understood by boulders; say from 4 to 8 inches in diameter—the sort of thing that used to be employed for pavements where flags were not available. These are here called

[1] Marr, *Deposition of the Sedimentary Rocks*, Cambridge University Press, 1929.
[2] Loc. cit. Chapters VII–IX.
[3] The divisions in the table may in fact be taken as approximating to a logarithmic scale.

cobbles.[1] The term *silt* indicates something between sand and mud: so fine that the individual particles cannot be seen without magnification, but not so fine that it becomes plastic when half dry, like clay, which geologically is partly dried mud. *Ooze* and *Red Clay* will be defined presently.

The first two divisions of the table do not need further explanation. The deposits of the shore-belt are often called *littoral*, which is merely a more pompous word for the same thing. The belt of variables may be taken as corresponding roughly with the surface of the continental platform, which as before explained often falls away sharply at a depth of about 100 fathoms, and the deposits formed on it show the greatest variety. Besides the normal sand and silt there are commonly large accumulations of organic remains of all kinds, mainly shells and other calcareous structures, carapaces of crustaceans and an endless variety of marine animals and seaweeds. Coral reefs, to be described later, really belong here. To cut this short, we may say that the constituents of future limestones are abundant in the belt of variables. It is an ancient fallacy that limestones were formed in deep water.

The Mud-belt.—The inner mud-line may be taken to coincide with the edge of the continental platform, and the outer mud-line, much more vaguely, with the foot of the continental slope. Below this come the abyssal depths, beyond the reach of land-derived material.

Murray and Renard distinguished three types of mud by their colour: of these *Blue Mud* is by far the commonest, being estimated to cover about 14,000,000 square miles of the sea-floor. When wet it is usually grey or black rather than blue, the colour being due to finely divided carbon or ferrous sulphide, or both, and a fresh sample often smells of sulphuretted hydrogen. Since the raw material of the grey and blue clays so common among ancient marine strata must have been similar to modern blue muds, their mineral constitution is discussed in Chapter IX.

Red mud is local in its distribution, being found only in such places as off the mouth of the Amazon where large quantities of sediment rich in red ferric oxide or hydrate are brought down by the river as a result of the lateritic type of tropical weathering (see p. 88).

Green mud, which is rather more widely spread than red mud, owes its colour to the mineral glauconite: the reason for its formation is not really understood, though it is abundant in several of the older formations and is fairly common also in the Belt of Variables, as greensand. The most important occurrence of green mud is on the Agulhas Bank, off the south point of Africa.

[1] Many of the old cobble pavements of East Anglian towns and villages contained most interesting collections of Scottish and Scandinavian rocks, ultimately derived from boulder clay, but generally obtained from local beaches and gravel pits.

Coral Mud. Around coral islands large quantities of highly calcareous mud, often nearly pure calcium carbonate, are formed by wave action and afterwards carried out into deep water.

All these varieties of mud contain large quantities of organic remains, calcareous, siliceous or chitinous, some easily visible and some microscopic: these may either disintegrate altogether or be preserved as future fossils. Besides the animals and plants living on the sea-floor there is a constant shower of the dead remains of floating or swimming organisms sinking to the depths.

The Oozes and the Red Clay.—Most text-books of geology contain long and detailed descriptions of the deposits found in the abyssal depths, the *oozes* and the *red clay*. Though of great interest to the biologist and the oceanographer, it is now realised that they are not of much importance geologically, since it is generally agreed that no representatives of them have been definitely identified among the older rocks. They will therefore be treated very briefly here. The general principle of their formation is as follows: as already pointed out there is in the sea a continuous rain of animal and vegetable remains, mainly calcareous or siliceous, sinking after death towards the floor: now both calcium carbonate and silica are soluble in water, the former much more so than the latter, and the solubility of both is increased by pressure, that is, by increasing depth. There is also a certain minute quantity of volcanic and other dust, derived from the atmosphere, and material from floating pumice, all of which are still less soluble. Consequently during descent there is a kind of sorting by differential solution: the calcium carbonate dissolves first, then the silica. Calcareous organisms reach very considerable depths, but not the greatest. Calcareous oozes are most common in warm seas, such as the Globigerine and Pteropod oozes of the Atlantic. But it should be noted that these also contain the siliceous organisms and the dust, masked by the abundance of *Globigerina*, etc. At greater depths all the calcium carbonate has been dissolved, and only the siliceous Radiolaria and Diatoms and the dust survive. For some reason diatoms are specially abundant in cold seas and diatom ooze is largely developed around the Antarctic continent, while radiolarian oozes are common in the deepest parts of the Pacific. Lastly we have the *Red Clay*, which is simply the dust, after all the rest has been dissolved out. This covers an enormous area in the great oceans. The slowness of its formation may be estimated from the fact that teeth of extinct species of shark have been dredged up from its surface: in millions of years not enough red clay has been formed to bury them.

It is evident that in regions such as the Newfoundland Banks, where icebergs are melting and dropping vast quantities of rock material derived from the land of their origin, the sediments forming on the sea-floor must be of a confused and highly complicated character.

The Forms of Marine Sediments.—The thickness of sediment laid down at any given point will evidently depend on several factors, of which the most important are the amount of material available, the depth of the water, and the character and force of waves and currents. If the supply of land-derived material is abundant the deposit will go on accumulating until its upper surface comes within the reach of wave and current action, and this forms the higher limit. Consequently a greater depth of sediment can accumulate on a steeply sloping shore than on a gentle one. Since the supply of material falls off as we pass farther out to sea, the deposits of terrigenous origin will thin out in that direction, so that on the whole they are wedge-shaped, with the broad end towards the land. But there is also a thinning at the landward end, so that the general form of marine terrigenous sediments must be somewhat as is shown in Fig. 60. The arrangement of the separate strata or layers of which the deposit is composed also depends on similar principles, so that, when regarded on a broad scale, the stratification of marine deposits is not strictly horizontal, but inclined, especially if the submarine slope is at all steep. The general structure of masses of

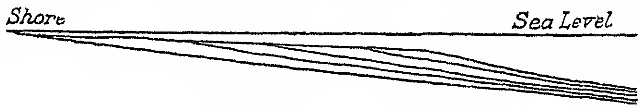


Fig. 60.—Formation of Shore Deposits.
Showing their thinning out away from the land.

land-derived sediment, if looked at in this way, is seen to have some resemblance to the formation of an embankment by tipping truck-loads of material over the end, which thus grows by addition of successive inclined layers. In this case the level upper surface on which the trucks run is represented by the horizontal or gently inclined lower limit of wave-action (see Fig. 60).

It follows from the foregoing considerations that, on the whole, the moderately coarse-grained shallow-water sediments deposited a short distance below low-water mark will be the thickest, while the muds and other deep-sea deposits are the thinnest; and this is borne out by actual observation of the relative thicknesses of the different types of sediment of the same age among the older rocks. Thick masses of shallow-water strata can often be traced laterally into deep-water muds or clays of moderate thickness, and these again sometimes pass into thin deposits showing some resemblance to those of the modern abyssal depths, but this analogy must not be pushed too far, since extreme thinness of deposits can be brought about in other ways, and lithological character and composition must also be taken into account.

The description of marine deposits here given is too much simplified to correspond exactly to reality since it assumes constancy of condi-

tions. As will appear in the chapter on earth-movements and in the stratigraphical part of this book, geological time is so long that within the limits of a single formation important changes can take place in the relative levels of land and sea: in particular, owing to a gradual depression of the sea floor, enormous thicknesses of shallow-water sediments can accumulate, which would obviously be impossible under constant conditions, while, owing to submergence of land, marine deposits can transgress far and wide over it. The subject is extremely complicated and cannot be pursued further here, but unless the existence of these slow, long-continued and extensive relative movements is realised, the next section, on Coral Reefs, is hardly intelligible.

Coral Reefs and Coral Islands.—The most conspicuous and most interesting calcareous formations of the present day are the coral reefs and coral islands so widely distributed in tropical regions. Reef-building corals can only live where the temperature of the water never falls below 20° C. (68° F.), hence they are almost confined to the regions enclosed by the parallels of 28° N. and S. Owing to the exceptional warmth of the waters of the Western Atlantic they extend to 32° N. in Bermuda. Corals do not flourish on the western coast of America; this may be owing either to cold return currents from the poles or to the great amount of mud washed down from the mountains of the Pacific slope. The greatest development of coral reefs is in the Western Pacific and Indian Oceans. Here they occur in vast abundance and exhibit their most characteristic forms.

Types of Coral Reefs.—The structures produced by reef-building corals are usually classified in a general way as fringing reefs, barrier reefs and atolls. Fringing reefs are those which are in visible continuity with the shore; barrier reefs are separated from the shore by a lagoon or channel of greater or less width and depth; while atolls are more or less complete rings of reef, at or near sea-level, without any central island. The origin of fringing reefs is fairly obvious; they are simply platforms extending outwards from the land in shallow water, composed of corals and other calcareous creatures; their upper limit is determined by the level of low tide, since corals cannot live if they are exposed to air and sun for more than a very short time. This reef-platform apparently extends seawards on a talus of its own material, and is often bounded on the outer side by a raised rim, consisting to a very large extent of Nullipores and other calcareous algae. The structure of the reef is frequently cavernous, and it is generally traversed by open channels opposite the mouths of streams; at these points the conditions are unfavourable to the growth of corals owing to the presence of fresh water and mud.

The origin of barrier reefs and atolls has given rise to a great deal of controversy, and even now perhaps the question is hardly settled. The essential structure of a barrier reef is very much like that of a

fringing reef, except that it is separated from the land by a lagoon or channel. Barrier reefs vary greatly in size: they may be a few yards or several miles in width, of almost any length, and often at a considerable distance from the land. The general explanation of the lagoon is that when a fringing reef around a subsiding island has attained a considerable width the growth of coral ceases in the inner parts: as the land subsides growth still continues actively at the outer edge, and if the subsidence is not too rapid, a reef continues to be formed at an increasing distance from the shore, thus gradually widening the lagoon. Solution also probably plays a part in deepening it, as the water often gets very hot. A noticeable and very important feature of islands with barrier reefs is that they do not show cliffs, but are deeply embayed by arms of the lagoon, showing what may be called a starfish outline. This is a clear proof of submergence—the drowning of valleys formed by ordinary stream erosion. It is similar to the formation of rias (see p. 145).

On account of its vast size the Great Barrier Reef off the coast of Queensland requires special consideration. It extends for about 1,000 miles, not continuously, but with frequent openings, some several miles wide; towards the southern end it becomes more and more discontinuous. In most places its distance from the coast varies between 50 and nearly 100 miles, though in one place it approaches within 7 miles. Parts of the reef itself are several miles wide, and the depth of the lagoon is usually between 10 and 25 fathoms. There are many islands, some of considerable height and composed of rocks similar to those of the near-by coast, as well as sand-cays and sand-spits.

It is obvious that a reef at such great distances from the coast cannot have been built up wholly by corals from the bottom of the sea, as described for barrier reefs on a small scale. The view now generally accepted is that the main element involved in the formation of the reefs is the faulting of a series of crust-blocks with downthrow away from the coast and attendant slow submergence, with which reef-upgrowth has gone on concurrently. It is not known how thick the coral is in the barrier. The faulted coast blocks in effect form a wide continental platform.[1]

Atolls.—Still more characteristic and peculiar are the atolls, which are more or less complete rings of reef enclosing a lagoon, without any central island (Fig. 61). The pictures of atolls in popular books are rather misleading, since they generally represent a continuous circular ring of land of uniform height and symmetrical structure. True atolls are rarely circular, and hardly ever possess a continuous ring of land above sea-level. Generally they consist of a submerged reef-platform of irregular shape, and on the rim of this arise a greater or smaller number of detached islands, which are often more or less continuous

[1] Steers, *Geog. Journ.*, lxxiv., 1929, p. 232.

or only separated by shallow channels. As a rule, land is more continuous on the windward side, and the leeward side is often completely

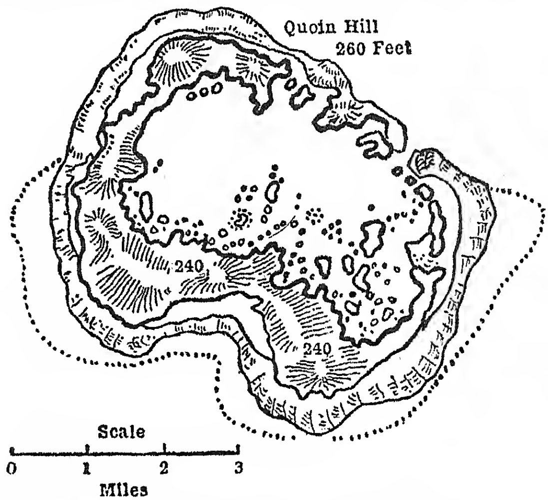


Fig. 61.—Limestone Atoll, Fulanga, in the Eastern Group of Fiji Islands (After Stanley Gardiner.)

without islands. Besides these shallow channels there are generally one or two passages into the lagoon deep enough for ships to enter. Only one or two instances of completely closed atolls are known, e.g. Niau in the Paumotu group, and Clipperton Atoll in the North Pacific.

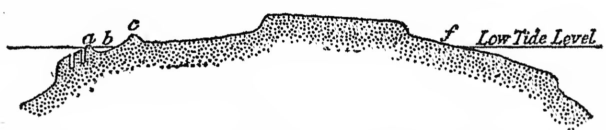


Fig. 62.—Section through Pava Island, Funafuti. (After Stanley Gardiner.) *a*, Rim; *b*, Reef flat; *c*, Rough zone, with pinnacle; *f*, Lagoon platform.

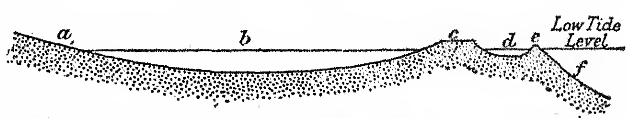


Fig. 63. Section through Reef. (After Stanley Gardiner.) *a*, Beach; *b*, Boat channel; *c*, Boulder zone; *d*, Reef flat; *e*, Rim; *f*, Outer slope.

The depth of the lagoon rarely exceeds 30 fathoms, but some are known as much as 50 fathoms deep. The dimensions of atolls are very variable, from a mile or so up to 90 miles in diameter. Frequently small atolls

are arranged around the periphery of a large submerged platform, as in the Maldives.

The structure of a typical atoll is somewhat as follows. In the centre is the lagoon with a flat floor, rising slightly near the margin towards the reef, which rises abruptly, often forming a submerged cliff a few feet high. The reef itself is essentially the same in structure as the barrier reefs above described, usually with a raised rim on the seaward side. Outside the actual ring of the reef comes a very rough surface, sloping down gently to a depth of about 40 fathoms, the so-called reef-platform. This passes abruptly into a *steep*, at an angle often exceeding 50° and sometimes as high as 75°. At about 140 fathoms this steep begins to pass gradually into the contour of the sea-bottom.

Origin of Atolls : Darwin's Theory.—The earliest explanation offered to account for the existence of atolls was that they were formed around the craters of submarine volcanoes. However, this was soon seen to be inadequate, although it is undoubtedly true in one or two cases, e.g. Totoya and Thombia in Fiji. The whole subject was investigated by Darwin [1] during his memorable voyage in the *Beagle*, and on the observations then made he founded a theory which is widely accepted. According to Darwin, fringing reefs, barrier reefs and atolls are three successive stages in the growth of corals round a slowly sinking land-area, so that the growth of the reef was able to keep pace with the subsidence.

It is a matter of observation that the growth of the reefs is most active on the outer margin ; and Darwin supposed that, as the island sank, the growth of the corals was upward, and to a certain extent outward, on a talus slope of their own débris. Commencing with a fringing reef, as the island sinks and becomes less the reef becomes more and more distant from the shore, first forming a barrier reef with a channel inside it, and eventually, when the whole island has disappeared beneath the waves, a circular ring of coral is left, with a shallow lagoon inside it, forming an atoll.

Funafuti.—In the early nineties a committee of the Royal Society investigated the structure of a typical atoll—namely, Funafuti—in the Indian Ocean. Borings were put down to a depth of about 1,100 feet, passing entirely through coral rock, more or less converted to dolomite. This great thickness is in itself indicative of subsidence, but it is not conclusive, since it was not possible to determine with certainty whether the rock consists of coral in the position of growth or of talus material.[2] This difficulty is largely due to the extensive chemical changes that have taken place in the rock, obscuring the structure.

Alternative Theories.—Later investigators pointed out certain

[1] Darwin, *Coral Reefs*, 3rd edition, 1889.

[2] 'The Atoll of Funafuti,' *Report of the Coral-reef Committee of the Royal Society*, London, 1904.

objections to the subsidence theory, the most important being the common occurrence of elevated reefs in many islands of the Pacific. Sir John Murray suggested that atolls had been built up on the tops of volcanic islands reduced below sea-level by wave erosion, forming submarine platforms at a depth of something like 30 fathoms. Others, of whom Prof. Stanley Gardiner may be quoted as an example, suggested that chance elevations on the sea-floor might be built up by calcareous organisms other than reef corals to such a height that corals could begin to build on them.

Another explanation that attracted wide attention was put forward by Prof. R. A. Daly, who pointed out that during the Great Ice Age a large amount of water must have been removed from the sea to form the great ice-caps, thus lowering the general sea-level. Under these conditions oceanic islands would undergo denudation to a depth corresponding to the lowered sea-level and when the water returned at the end of the cold period and became warmer from the general rise of temperature, corals would begin to build on the submerged banks thus formed. An important feature of most of these theories is that the base of the mass of reef-coral would be flat. The significance of this will be discussed shortly.

Raised Coral Reefs.—Explorations in many parts of the Pacific have proved the existence of coral reefs of recent date at all elevations up to at least 1,000 feet above sea-level. Such occur, for example, extensively in Fiji, as shown by Foye,[1] and in the Tonga Islands, as described by Lister.[2] This group consists of platforms at three distinct heights, at approximately 140, 300, and 500 feet above sea-level. One small island has a remarkable basin-shaped top with a flat rim, and is obviously a raised atoll. In the islands of Kambara and Wangava, in the Lau Islands, the S. E. portion of the Fiji group, there are raised rims of this kind 260 and 300 feet high respectively on the inner side. Another very interesting case is Christmas Island, described by Andrews.[3] This is the flat summit of a volcano, more than 15,000 feet high from its base on the sea-floor, of which nearly 1,200 feet is above sea-level. Forming the upper part of the island are limestone terraces, ranging from Eocene to Recent, with volcanic rocks below, and also interstratified with their oldest members. The succession of events seems to have been as follows: First a gradual depression, leading to the formation of the Tertiary limestones; then a period of rest followed by successive elevations, giving rise to the present terraced structure. A long pause between the downward and upward movements led to the atoll condition for a while.

[1] Foye. Geological Observations in Fiji, *Proc. Amer. Acad. Arts and Sci.*, liv., 1918, p. 1.
[2] Lister, *Quart. Jour. Geol. Soc.*, xlvii., 1891, p. 590.
[3] Andrews, *A Monograph of Christmas Island*, 1900.

Modern Views on Reef-formation.—By far the most important contribution to this subject during the present century is due to Prof. W. M. Davis of Harvard. Most of the work was done in 1914, but the book was not published till 1928. After an exhaustive study of the literature Professor Davis went to see for himself, and what he saw convinced him of the essential truth of Darwin's subsidence hypothesis : some of the strongest evidence was derived from the study of elevated reefs, the cause of so much doubt to earlier workers. One of Davis's main points, the embayed character of reef encircled islands, has already been mentioned. Another is based on the nature of the contact between the reef and the underlying rock, which obviously can only be seen on raised reefs. In several cases this contact was found to be an unconformable overlap (see p. 18 and Fig. 8) a relation which can only be produced by transgression of the sea during submergence.[1]

It is, of course, obvious that the arguments from embayed coastlines and unconformable contacts cannot be applied directly in explanation of atolls without central islands, since neither phenomena can there be seen. But atolls are so like the barrier reefs round islands that the argument from analogy probably holds good, and the same explanation may be applied.

It may be concluded, therefore, that coral reefs are formed during submergence of land, and that Darwin's theory now holds in all essential points with such modifications as are required by later work. It is clear that the submergence was not uniform, as he supposed, but very local, and in some cases it can be shown that single groups of islands have been tilted about an axis ; thus the occurrence of local raised reefs presents no obstacle to the acceptance of Darwin's theory in its most general form.

[1] Davis, *The Coral Reef Problem.* New York, 1928.

CHAPTER IX

THE SEDIMENTARY ROCKS

Introductory.—As a result of the processes of denudation and deposition briefly described in the foregoing chapters, there have been accumulated during past ages masses of material which in course of time have been more or less completely consolidated and converted into what are popularly known as *rocks*. All masses formed in this way are known as the *sedimentary rocks*, in contradistinction to the *igneous rocks*, which have solidified from a state of fusion.

It is perhaps necessary to point out that the term sediment is used in geology in a very broad sense, to include some deposits not conforming to the strict dictionary definition of the word, as solid material settling down in water. But it is found that every other term suggested is open to a similar kind of criticism and some of them are very pedantic. The expression sedimentary rocks can in reality only be defended as less open to objection than any other hitherto proposed; but it is now almost universally adopted and understood in this broad sense.

Classification of the Sedimentary Rocks.—The classification here adopted is essentially based on the discussion of modern marine deposits in Chapter VIII, especially the table on p. 150. Although this is strictly only applicable to deposits formed in the sea, yet those formed in fresh water and on land are so similar that the scheme can be extended to them also: sometimes it is only possible to decide by means of fossils whether a given rock was originally marine, fresh water or terrestrial.

Hence for the first few groups at any rate the classification is mechanical: that is to say, its basis is simply the size of the components, irrespective of their composition. It is obvious that the pebbles in a gravel, for example, may consist of any kind of rock, according to their original source, and in the same way the fine-grained deposits may be composed of crystals or parts of crystals of any mineral, or even of amorphous material. Distinctions founded on the nature of the components of the various classes will appear in the detailed discussion in the following pages. The calcareous rocks and a few other types differ in important respects from the mechanical sediments and have to be dealt with on other lines, as will appear later.

Referring again to the table on p. 150, we find that the chief constituents of the mechanical sediments are—boulders, cobbles, gravel, sand, silt and mud. (The question of the actual limits of size to be adopted will be discussed later.) When consolidated these form what

may be called as a preliminary, boulder and pebble-rocks, sand-rocks, and mud-rocks. But in geology it is unfortunately not customary to use such plain Anglo-Saxon words as these: they have to be translated into a pseudo-classical 'scientific' jargon. We thus arrive at the following nomenclature:

Rudaceous class = boulder, pebble and gravel-rocks.
Arenaceous class = sand-rocks.
Argillaceous class = silt and mud-rocks.

The Rudaceous Rocks.—This class comprises all the mechanically formed sedimentary rocks with constituents larger than sand. At the outset two points arise for consideration: firstly, what size limits are to be adopted, and, secondly, the fact that the coarse-grained sediments are not usually so well sorted that all their constituents are of the same size. There have been endless discussions of the size-limit between fine gravel and coarse sand: the general opinion seems to be that the line should be drawn at about 2 mm. With regard to the second point it would seem that the size of the largest components should be the criterion. Examination of any gravel-bed, ancient or modern, will show that there are always or nearly always gradations in size, the spaces between the larger pebbles being occupied by smaller pebbles and sand. The limit between cobbles and boulders might be chosen arbitrarily at somewhere about 6 inches greatest diameter.

In mechanical sediments laid down in water the larger pebbles at any rate are commonly well rounded, in marine gravels perhaps rather more so than in river gravels. In terrestrial deposits, however, such as screes, the blocks are usually angular. In ordinary nomenclature a distinction is drawn between these two types, when consolidated, those with markedly angular components being called *breccias*, and those with rounded ones *conglomerates*. These terms may, if necessary, be qualified by reference to the character of the components, such as limestone-breccia, or flint-conglomerate. In many instances much interesting information as to the sources of the material has been obtained from petrographical study of the pebbles in conglomerates, which has been of great value in stratigraphy and the reconstruction of the geography of past ages.

Since the nature of the binding materials or *cement* of the rudaceous rocks is essentially the same as in the arenaceous group and is more easily studied microscopically in the finer grained types, discussion may be deferred to the next section.

The Arenaceous Rocks.—This group includes the more or less consolidated representatives of the modern sands, of whatever origin. It has already been stated that the upper limit of grain size is now usually taken at about 2 mm.; the lower limit is about that of naked-eye visibility, or approximately 0·05 mm. One notable point has also been referred to, namely, that grains so small as this usually consist

of single crystals or parts of crystals of definite minerals, though minute compound grains of very fine textured rocks are often found. Again, the constituents of sands usually are, or appear to be, better graded or sorted than the coarser types, often being remarkably uniform in grain-size.

The principal points needing discussion in connexion with the sand-rocks are: the mineral composition of the grains; their form; and the nature of the binding material, or cement, if any. The first two of these often afford information as to the origin and manner of formation of the original sands.

Some of the less ancient stratified rock-systems include beds of sand still almost or quite unconsolidated, but much more commonly and in the older systems almost universally they have been more or less cemented and sometimes they are very hard indeed. The cementing material is probably always introduced by percolating water.

The most common cementing substances are silica, carbonate of lime, and some forms of iron oxide, either anhydrous or hydrated. These are spoken of as *siliceous*, *calcareous* and *ferruginous* cements respectively. According to the character of the mineral particles and the nature of the cement various special names are applied to the different rock-types.

Sand.—This name is applied to the loose incoherent aggregates of mineral particles of sufficient size to be easily visible to the naked eye. Sand-grains may be either *simple*, consisting of one crystalline individual or part of such; or they may be *compound*, composed of aggregates of crystals of one or more minerals; the latter kind of grain may also be defined as a rock-particle. Sands also often contain shells and other structures of organic origin, either whole or broken, and often finely comminuted. By far the most abundant of the minerals composing all ordinary sands is quartz, since this substance is hardly affected by any of the ordinary weathering agents, whereas most of the other common rock-forming minerals are easily destroyed by weathering. After quartz, the most abundant constituents of sands are flakes of white mica, grains of felspar, and more or less rolled crystals of the minerals of the igneous and metamorphic rocks. Since the minerals of the latter groups have, as a whole, a considerably higher specific gravity than quartz or felspar, they are easily separated for examination by means of dense liquids in which the quartz and other light grains float, while those of a higher density than the liquid sink to the bottom. The study of the heavy minerals of the sedimentary rocks has of late years become an important and fruitful branch of petrology, and it has in some cases thrown a considerable amount of light on the sources from which the materials were derived. Some of the most important of the minerals identified by this method are zircon, tourmaline, garnet, cassiterite, rutile, anatase, brookite,

andalusite, kyanite, sillimanite, staurolite, fluor-spar, sphene, magnetite, ilmenite and muscovite.

It is unnecessary to give any detailed account of the compound grains in sands, since they may consist of fragments of rock of any kind whatever ; however, as would naturally be expected, the most abundant are fragments of the hardest rocks, and especially rock in which quartz is a prominent constituent.

The size and form of sand-grains vary according to the conditions under which they are formed, and it is scarcely possible to lay down any definite rules ; but, broadly speaking, it may be said that sands formed in water usually consist of subangular grains, that is, grains of

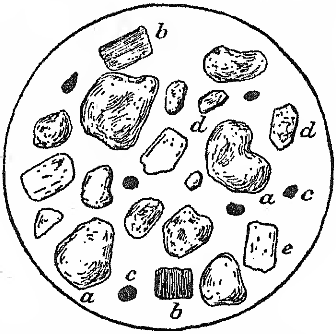


FIG. 64.—MODERN BEACH SAND.
a, Quartz ; *b*, Tourmaline ; *c*, Magnetite ; *d*, Zircon ; *e*, Glaucophane.

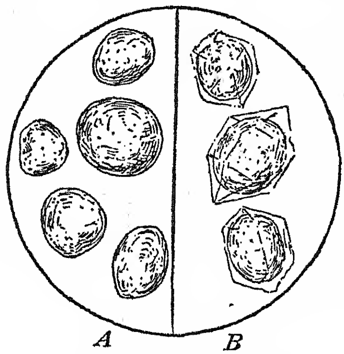


FIG. 65.
A, Millet-seed sand-grains ; *B*, Grains from the Penrith Sandstone, showing secondary growth of silica with crystal faces in optical continuity.

more or less angular form with their corners rounded off : in desert sands, on the other hand, the grains are often very completely rounded, both large and small alike : such are often spoken of as millet-seed sand (Fig. 65, *A*). In some water-formed deposits in which the grains vary a good deal in size, it is often noticeable that the larger grains are much more rounded than the smaller ones. It is generally stated that sands of glacial origin possess sharply angular grains, owing to the absence of any rolling motion, but of course it is obvious that ice may pick up sand-grains of any shape from older formations. It is a point often not sufficiently made clear that the constituents of sands, and indeed of gravels also, may be passed on from one geological formation to another almost indefinitely without much change of shape.

When a sand is consolidated into a rock by a process of cementation, different names are applied according to the nature of the cement, the amount of hardening undergone and the nature of the constituent grains.

Sandstone.—When the cement is small in amount or very soft, so that the rock is easily crushed, it is called a *sandstone.* Many sandstones harden considerably on exposure to air, owing to oxidation or dehydration of the cement. In white sandstones, the cement is usually silica, less often calcium carbonate, while the yellow and brown colours so often seen are due to a cement of hydrated iron oxide. Red sandstones, which seem to be usually of terrestrial origin, have a cement of ferric oxide, often forming a pellicle round each grain, and easily removed by boiling in acid, leaving colourless grains of quartz and other minerals.

Quartzite.—When a rock consists chiefly of grains of quartz cemented by silica into a hard continuous mass, it is commonly called quartzite (see Fig. 66). The same name is also applied to sandstones recrystallised by heat into a mosaic of quartz grains without definite outline; hence some confusion inevitably arises.

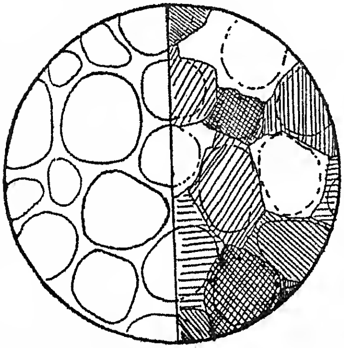


FIG. 66.—QUARTZITE.

A, In natural light; *B*, Between crossed nicols. The interspaces between the grains are filled with a secondary outgrowth of quartz in optical continuity. The shading is diagrammatic, indicating different interference tints.

Grit.—This name was originally applied to hard rocks consisting of sand grains mixed with small pebbles; such rocks break with a very rough surface and are suitable for millstones. Of late years the term has been extended to include almost any type of hard arenaceous rock, irrespective of texture, such as are so common in many of the older rock-formations.

Calcareous Sandstone.—When the cement consists of calcite, so that the rock is composed of grains of quartz, etc., embedded in crystals of calcite, which often show their characteristic cleavages when broken, it is called a *calcareous* sandstone (or grit).

Arkose.—This name is applied to a sandstone or grit with a large proportion of felspar; the cement is usually siliceous. Arkoses or felspathic grits often result from the denudation of large areas of crystalline rocks of igneous or metamorphic origin.

Greywacké.—This is a somewhat old-fashioned term often applied to the grey or greenish grits characteristic of the older sedimentary formations. They usually contain a good deal of material of volcanic origin, and they graduate into the true volcanic ashes.

Flags.—In many formations there are found rocks of the arenaceous class with a large proportion of thin flakes of white mica. These flakes

generally lie parallel to the bedding planes, and in consequence the rocks split readily into slabs parallel to these planes. These are called *flags*. This name is also applied to many thin-bedded sandstones with little or no mica, which break up readily into flat slabs, the discontinuities in this case being due to pauses in deposition.

Finally, a few words must be said on the silt rocks. The usually accepted size-limits here are 0·05 mm. and 0·005 mm.: hence the individual grains are invisible to the naked eye and the rocks can only be distinguished microscopically from the mudstones of the argillaceous group. Nevertheless, they are micro-sandstones, micro-flags, etc., the constituents being the same as in the coarser types, and they do not possess some of the characteristic properties of argillaceous rocks, to be discussed later, such as plasticity when partly dry, and so on. The silt rocks are therefore to be regarded as in many ways intermediate between the arenaceous and argillaceous groups.

The Argillaceous or Mud Rocks.—In this group are included the finest types of land-derived sediment, laid down in the sea and in some fresh-water lakes, as well as certain terrestrial deposits of extremely fine grain (dust deposits). Taking as usual the marine sediments as typical, it has already been shown that at a certain indeterminate but not very great distance from the shore-line, the inner mud-line, the sands and silts pass into muds. The transition is of course quite gradual, but it is a fact that when a certain limit of grain size is passed the sediments show quite definite differences of character. Even fine silts and their derivative rocks are essentially similar to the sands and their derivatives, consisting of very finely divided but chemically unaltered minerals (rock-flour). But the muds in the true sense contain not only materials of this kind still more finely divided, but also products of the chemical weathering of the land surface, some crystalline, but some in the amorphous or colloidal state. Of late years a great deal of work has been done on the constitution of this latter kind of material, but the results are not yet wholly satisfactory and in the present state of our knowledge it is best to use the vague and non-committal term *clay substance*. When any considerable proportion of this is present the deposits show certain characteristic peculiarities, especially the property of plasticity.

Mud.—In normal fresh muds, as just stated, both rock-flour and clay substance are present, but owing to the very small size of the particles, it is difficult to determine how much of each, but those laid down in glacier-fed lakes and the terrestrial dust-deposits are mostly made up of rock-flour. In water-formed muds the proportion of mica is higher than in the sandy rocks, since owing to their large surface mica-flakes sink more slowly and are carried farther from the shore than quartz-grains of the same weight. A good deal of the clay substance also seems to resemble mica in its physical properties, though

some of it is amorphous or colloidal (jelly-like). Muds also usually contain more or less carbonaceous material derived from the decomposition of organisms and in some marine muds finely divided ferrous sulphide is abundant.

The colours of the different varieties of marine muds and their significance as to conditions of origin have already been discussed in Chapter VIII. These differences are naturally preserved in their solidified representatives, and afford information as to the geography of ancient times. In the past, as at present, blue mud was by far the most common type.

The muddy sediments were consolidated, not like the sandy deposits by cementation, that is by introduction of secondary material, but mainly by loss of water and compression due to the weight of overlying strata. Consequently they show less variation of type than the arenaceous group.

Clay.—A very common type of sediment, especially among the younger formations, is formed by the compression and partial drying of mud. This is known as *clay*. The compression is usually effected by the weight of overlying strata, and it is accompanied by loss of water, so that the material decreases in bulk and becomes plastic. In true clays no particular structure is developed, and the mass is usually traversed by irregular cracks due to shrinkage, so that it breaks with a more or less conchoidal fracture. The colours of clays depend on the state of oxidation of the iron content. Besides the true sedimentary clays there are other special types of argillaceous rocks of different origin. Some of the most important of these are—China-clay, formed by the decomposition of granite *in situ*; Loess, a pale calcareous clay found in Central Europe and Asia over large areas, probably formed by wind-blown dust; Boulder-clay, an accumulation of glacial origin, consisting of pebbles and boulders, often scratched, embedded in a matrix of clay and finely divided rock-material.

Mudstone.—When a clay has been so much hardened by drying and compression that it has lost its plasticity, it is known as *mudstone*. A true mudstone shows no definite structure, except that it is often traversed by joints in various directions, owing to shrinkage.

Shale.—When an argillaceous rock shows a tendency to split readily into thin slabs parallel to the original bedding, it is called *shale*. This structure is known as *lamination* (see p. 16). It appears that besides the mechanical rearrangements involved in the formation of shale, there is also a considerable amount of mineralogical change, and especially production of a secondary micaceous mineral, which facilitates the splitting. Many clays, mudstones and shales contain a good deal of pyrite, often in crystals of considerable size. This mineral is formed by reduction of iron oxides by organic matter which generally contains a good deal of sulphur, and the dark colour of many shales is supposed

to be due to finely disseminated iron sulphides, while in others it is due to carbon.

Slate.—Very many argillaceous rocks, especially among the older formations, have undergone a further change in the development of new planes of division, or cleavage planes. Such rocks are known as *slates*, and will not be further described here. The general character of *cleavage* has been dealt with in the introduction, while the rocks themselves strictly come under the heading of metamorphism (see Chapter XII).

The Calcareous Rocks.—Under this heading are included a large number of rock-types of diverse origin and varying character, which agree in the fact that they contain a notable proportion of calcium carbonate. Many of the calcareous rocks are of organic origin, being composed for the most part of the more or less altered remains of animals and plants with a calcareous shell or skeleton. Since these are almost exclusively inhabitants of the sea or of fresh water, it follows that the calcareous organic sediments are chiefly of aqueous origin. Besides these organic sediments, some important types of calcareous rocks are formed by various inorganic processes, both mechanical and chemical, as will be hereafter explained. Many of the calcareous rocks differ from those of the classes hitherto described in that they do not pass through an unconsolidated stage, but are originally deposited in a coherent form. This statement applies to rocks of both organic and inorganic origin. The great majority of the rocks of this group come under the somewhat vague general designation of limestones, but special names are also applied to many of the varieties, and as a matter of convenience some rocks which are not strictly calcareous are also included here.

Calcareous Muds and Oozes.—Perhaps the simplest examples of unconsolidated calcareous deposits are afforded by the coral muds and deep-sea oozes now being formed in the deeper parts of the oceans and in the regions surrounding coral islands. These have already been described, and need no further reference here (see p. 151). In many fresh-water lakes also there are to be found deposits of a muddy nature containing a considerable proportion of calcium carbonate.

Shell-sand and Shell-banks.—In the shallow seas surrounding land-areas there are frequently to be found enormous accumulations of dead shells, either whole or broken. Such shell-banks and shell-beaches are common on the Atlantic coasts of Britain, and especially on the coast of Holland, and these accumulations depend on the direction of the prevailing winds, which in this area blow most persistently from the S.W. and W. Dredging operations have also shown that the floor of the Irish Sea, the English Channel, and other seas on the continental platform is covered with a deposit consisting very largely of finely comminuted shells, mixed with a greater or less proportion

of sandy sediment. These deposits are commonly known as shell-sands.

Shelly Limestones.—When masses of whole or broken shells, such as were described in the preceding paragraph, are cemented into a solid rock they form shelly limestones, such as are common at many stratigraphical horizons. The cement in this case may consist either of finely divided calcareous mud, formed at the time of deposition and subsequently hardened by drying, or of crystalline calcite deposited at a later date by percolating water. There is often a considerable amount of ferruginous material in such a cement, and to this is due the yellowish or brownish colour of certain limestones. Shell-banks, such as those now forming on the British and Dutch coasts, give rise to beds like some of the Pliocene 'Crags' of Norfolk and Suffolk, which are masses of shells more or less consolidated by a calcareous or ferruginous cement.

Coral Rock.—This is a variety of limestone consisting to a large extent of the remains of reef-building corals and other organisms. The character, distribution and origin of modern coral-reefs and coral islands have been discussed in detail in an earlier chapter, and it must suffice here to say that fossil coral-reefs of an essentially similar character occur to a considerable extent among the stratified rocks of various periods.

Crinoidal Limestone.—The Crinoidea, a class of the phylum Echinoderma, play a small part at the present day, but in the past they were of great importance as rock-formers, and enormous masses of limestone were built up to a great extent of their remains. A notable example is afforded by the Carboniferous Limestone of Britain. Modern echinodermal deposits are, however, being formed to a considerable extent in the Irish Sea.

Chalk.—This name is applied to a peculiar rock-type characteristic of the upper part of the Cretaceous formation of North-western Europe and elsewhere. It is a white, grey or yellowish rock of varying hardness, and usually of fine texture. It varies somewhat in composition, but usually consists to a large extent of finely divided calcareous mud with a greater or less proportion of recognisable organic remains, including Foraminifera, especially *Globigerina*; minute fragments of molluscan shells, especially *Inoceramus*; together with fragments of corals and sponge spicules, both siliceous and calcareous. Foreign detrital matter is not abundant, and Chalk often consists of nearly pure calcium carbonate.

Marl.—This rock is intermediate in composition between the argillaceous and calcareous rocks; it includes various types of calcareous clays and argillaceous limestones. The Chalk-Marl of Cambridge is a good example of the class: it contains clay and calcium carbonate in very nearly the right proportions for the manufacture of Portland cement, and is the basis of an important industry. Marls are very

commonly laid down in fresh-water lakes, and often contain abundant remains of gastropods, crustacea and fresh-water algae.

Unfortunately the term *marl* has often been applied as a more or less popular term to deposits which do not properly belong to this category. Thus much of the so-called Trias Marl of the Midlands really consists of very fine-grained red sands or silts.

The Microscopic Structure of Limestones.—Most of the fragments of calcareous organisms forming limestones possess peculiarities of structure which enable us to assign them to their proper zoological position. The most important of them are Foraminifera, calcareous Algae, Corals, Echinoderms, Polyzoa, Brachiopods, Lamellibranchs, Gastropods, and Cephalopods, while the limestones of the older geological formations naturally contain remains of organic types now extinct, such as the Trilobites and the Graptolites. In many limestones also there is a greater or less proportion of calcium carbonate in a very fine state of division, showing little or no definite structure and therefore of uncertain origin. It may be either very finely comminuted material derived from older limestones (calcareous rock-flour) or a chemical precipitate.

Calcium carbonate possesses two distinct crystalline forms, calcite and aragonite, with different physical properties. Aragonite is unstable under ordinary conditions, and is frequently either recrystallised as calcite or removed altogether by solution. Hence aragonite shells are often represented by mosaics of recrystallised calcite or by hollow spaces. In course of time the calcite of limestones also undergoes more or less recrystallisation, so that the original structure is often obscured; and some limestones have been more or less completely recrystallised, or converted into marble, without the help of any metamorphic agencies. For an account of the effects of heat and pressure (metamorphism) on limestones, see Chapter XII.

Most limestones contain more or less detrital matter of inorganic origin, according to the conditions under which they were formed; these impurities are usually of a sandy nature, consisting of grains of quartz, felspar and other minerals of the mechanical sediments. Glauconite also is not uncommon.

Many limestones of all ages also contain a considerable amount of iron, often as ferrous carbonate, siderite, forming part of the cement or partly or wholly replacing calcareous fossils. In fact, there is really every gradation from pure limestones to workable ironstones, as will appear later. Such ferruginous limestones weather to a rusty appearance and eventually give rise to brown or red soils.

Oolitic Structure.—Many large masses of limestone possess a peculiar and characteristic structure, being composed of rounded grains having somewhat the appearance of the roe of a fish, and from this the name *oolite* is derived. When the grains are of considerable size, as big as a pea, the rock is known as *pisolite.* Oolitic grains or *ooliths* usually

consist of concentric coats of calcareous material, either calcite or aragonite, arranged round a nucleus, which may be either a minute shell fragment, a sand-grain, or merely a pellet of calcareous mud. Besides the concentric coats there is often a more or less conspicuous radial arrangement of the minute elements of the grain. Sometimes the grains are compound; that is, two or more small grains may be enclosed in one outer coat. Sometimes the material has been recrystallised, so that the concentric and radial structures are destroyed, and aragonite grains are recrystallised as calcite. Oolitic grains appear to be formed in several different ways. Some are evidently concretionary structures of mechanical origin, due to the deposition of layers of calcium carbonate round a nucleus in a saturated solution. This process probably goes on in shallow water under the influence of current-action, which assists the production of rounded forms. It is clear, however, that in many cases calcareous algae play an important part in their formation, as for example in the Sprudelstein of Karlsbad and the oolitic sand of the Great Salt Lake. Many grains show under the microscope layers of tubular structures; these are referred to a problematical organism, *Girvanella,* which may be a simple form of calcareous alga.

Limestones of Mechanical Origin.—Certain beds of limestone with a nodular or pisolitic structure appear to be of mechanical origin in their present form. They are composed of fragments derived from pre-existing limestones, and are not due directly to organic agency. They are therefore to be regarded as shallow-water sediments formed in areas where large masses of calcareous rocks are undergoing denudation. Such appears to have been the origin of the Cornstones of the Old Red Sandstone of the Welsh border, and probably also of the Lias limestones of Dorsetshire, where the rapid alternation of thin beds of shale and limestone almost precludes the possibility of direct organic agency. Probably many calcareous beds, showing little or no definite structure, were formed from calcareous mud of detrital origin.

Travertine and Calc-sinter.—Calcium carbonate is almost insoluble in pure water, but when it is acted on by water containing carbon dioxide a reaction occurs, and a bicarbonate is formed, thus—

$$CaCO_3 + H_2O + CO_2 = H_2Ca(CO_3)_2.$$

This bicarbonate is soluble in the water to a much greater extent than the simple carbonate. Since all natural waters contain carbon dioxide, the waters percolating through limestone rocks become saturated with the bicarbonate. The amount dissolved also increases with the pressure. It is to be noted that heat diminishes the solubility, since the carbon dioxide is driven off and the normal carbonate is again formed. The waters of many springs become charged with the bicarbonate under considerable pressure, and when the spring reaches the surface the release of pressure, together with a certain amount of

evaporation, causes the normal carbonate to be re-formed and deposited. This gives rise to a spongy calcareous deposit often known as *tufa*. In the same way the water dripping from the roof of limestone caves undergoes evaporation and deposits carbonate of lime. This gives rise to peculiar forms, generally having an elongated shape and concentric structure. When these hang down from the roof of the cave they are known as *stalactites*, and the corresponding structures rising from the floor are called *stalagmites*.

The largest and most important of this class of deposits are those formed by hot springs, and to these the general name of *travertine* or *calc-sinter* is applied. In this case the process of deposition is not merely evaporation, but the separation of the carbonate of lime in the solid form has been shown to be effected by algae, which live in the heated water and deposit the carbonate in their tissues. The exact way in which this is effected is not understood. One of the best examples of this type of sinter is afforded by the Mammoth Hot Springs in the Yellowstone Park. Large deposits of travertine also occur at Rome and in other parts of Italy. The Sprudelstein of Karlsbad is also formed by algae, and this shows a very perfect example of oolitic structure, in which the grains consist of aragonite.

In some cases it is believed that calcareous deposits of this kind are due to actual chemical reactions between two solutions, as at Mono Lake in California, and this process may have occurred in some of the salt lakes of past ages.

Dolomite-Rock or Magnesian Limestone.—Closely allied to the true limestones is a rock consisting essentially of the carbonates of lime and magnesia. This is known as *dolomite* (more correctly *dolomite-rock*), or sometimes magnesian limestone. The magnesium carbonate occurs in varying proportions up to a maximum of about 44 per cent. This corresponds to the molecular ratio $CaCO_3 : MgCO_3 = 1 : 1$, and a rock of this composition consists entirely of the mineral dolomite, a double carbonate having the formula $CaMg(CO_3)_2$. A lower proportion of magnesium carbonate indicates an admixture of calcite or aragonite with the dolomite.

The origin of dolomite-rock has given rise to much discussion, but the subject is very complicated and cannot here be treated in detail. In a few instances, as in the Middle Trias of Thuringia and Württemberg and in the Tirol, beds of dolomite-rock are found associated with gypsum and rock-salt in such a way as to leave little doubt that they were formed by evaporation of water in closed basins. It is also believed that the Precambrian dolomite-rocks of the Canadian Rockies were in large part formed as chemical precipitates.

However, it is clear that the greater part of the dolomite-rocks of the older formations were originally sedimentary limestones enriched in magnesium at a later date, in many instances not long after their

original deposition. The Magnesian Limestone, which forms a large part of the Permian of northern England, contains marine fossils and is believed to have been laid down in an inland sea, something like the Caspian, which was gradually drying up. In places it includes important deposits of anhydrite.

Most large masses of limestone are more or less dolomitised, at least locally, and in some instances the process is almost complete, as for instance in the Tirol, where beds of dolomite-rock of Triassic age reach a thickness of several thousand feet and afford some wonderful scenery. These beds afford abundant evidence of having been formed from coral reefs. Some modern coral reefs are also more or less dolomitised. A most careful examination of the core from a boring put down to a depth of 1,100 feet in the atoll of Funafuti in the Indian Ocean showed that the lower part was almost completely converted to dolomite, whereas the upper part was calcite and aragonite. This must have been brought about by reaction between the coral rock and the magnesium salts of the sea-water while the reef was being built up on a sinking sea floor.[1]

It is noticeable that in many places where the Carboniferous Limestone of England has been overlain by Triassic strata it is more or less completely converted to dolomite-rock, especially along major joints and near fault-planes. This is obviously due to percolation of solutions containing magnesium salts derived from the Triassic strata above. In many places also the Carboniferous Limestone is dolomitised in the neighbourhood of important deposits of lead and zinc ores, also suggesting the influence of mineralising solutions.

Ironstones.—Iron is one of the most widely distributed of all metals throughout the visible portion of the globe, and rocks containing a notable proportion of this metal in the form of various compounds occur in innumerable localities. These rocks are of special interest owing to their great commercial importance. They have been formed in several different ways, some having been deposited very much in their present form, while others are evidently due to alteration of rocks originally of different composition. Some masses of ironstone are directly due to igneous activity, and this class will not be further described here (see p. 278). The majority, however, are obviously of sedimentary origin, and many of them are closely connected with the calcareous rocks.

Workable deposits of ironstone are found in rocks of almost all ages, and have naturally been formed in many different ways. In many cases, including some of the more important ones, the origin is still obscure, and certain theories, till lately widely accepted, have broken down under more critical examination.

The most extensive bodies of iron-ore now worked are those found

[1] See Skeats, *Quart. Jour. Geol. Soc.*, lxi., 1905, p. 97.

in the Precambrian formations around Lake Superior, mostly on the southern side. Vast thicknesses of these ancient rocks consist, when unaltered, of highly ferruginous cherts, with ferrous carbonate and green iron-silicate rocks, basic lavas and intrusions. In places where structures were favourable, the rocks have been deeply weathered at some long-past date, the silica especially being leached out and the iron, which is less soluble, being concentrated into a residue. Still later, owing to metamorphism, the iron compounds, originally hydrated, have been converted into haematite or occasionally magnetite.[1]

Apparently of similar origin are the enormous masses of schistose ironstone (itabirite) of Brazil, some of which are nearly pure haematite, running up to 69 per cent. of metallic iron.

In West Cumberland and the Furness district of Lancashire there are found great masses of haematite in Lower Carboniferous strata. These masses are generally quite irregular in form, and have clearly been formed by replacement of the calcium carbonate of limestone by iron derived from solutions that percolated through from red Triassic sandstones above.[2] The iron ores of Northern Spain (Bilbao) were formed in a similar way, but the source of the iron is here unknown.

The most important iron ores of England and France are of Jurassic age, and show conspicuously the oolitic structure, as described in the section on limestones. It was till lately believed that these were originally oolitic limestones, the calcium carbonate having been replaced first by iron carbonate, which afterwards underwent a more or less complete process of oxidation and hydration. However, recent researches have shown that a large part of the iron in these rocks now exists as a green silicate, and that the iron carbonate, which is also common, is mainly primary.[3] Other points of structural and chemical detail also, which cannot be described here, show that these rocks were originally deposited very much as they now are by some process of chemical precipitation in sea-water. The actual process, however, is unknown, and it is suggested, rather as a speculation, that bacteria played an important part in their formation.

In the Coal-measures, and in other strata of similar character, there occur beds of ironstone, often somewhat impure from admixture of earthy matter. These are variously known as *Black-band Ironstone* and *Clay Ironstone.* The iron usually exists in the form of carbonate; some of these may have been deposited very much in their present

[1] Van Hise and Leith, *The Geology of the Lake Superior Region*, Monograph 52, *U.S. Geol. Survey*, 1911.

[2] Bernard Smith, Spec. Rep. Min. Res. Gt. Britain: vol. viii, 'Iron Ores, Haematites of W. Cumberland, Lancashire and the Lake District' (*Mem. Geol. Survey*), 2nd edition, 1924.

[3] Cayeux, *Les Minerais de Fer oolithiques de France*, fasc. ii, Paris, 1922. Hallimond, Spec. Rep. Min. Res. Gt. Britain: vol. xxix, 'Iron Ores, Petrography and Chemistry' (*Mem. Geol. Survey*), 1925.

state, while others are due to metasomatism of more or less impure limestones. It is probable that some of the black-band ironstones are of essentially the same origin as the bog-iron-ore presently to be described.

It is clear that in many cases the separation of the iron from solutions is due, either directly or indirectly, to the action of vegetable matter, especially when in a state of decomposition. The action is complex, but the final result is the precipitation of hydrated oxides of iron, usually limonite. This process goes on in lakes and marshes, and gives rise to *Lake-ore* and *Bog-iron-ore.* The former is very largely developed in the shallow parts of some of the Swedish lakes. Of essentially the same character is the so-called Moor-band-pan, a hard layer often found in boggy ground between the soil and the subsoil. These processes may possibly be due to bacteria.

Salt Deposits.—In many parts of the world and at various geological horizons there are found large deposits of salts freely soluble in water under ordinary conditions. It is evident that their deposition and preservation are due to special circumstances, but it must not be supposed that this entails anything abnormal: such conditions have nearly always prevailed somewhere and are to be found in many places at the present time. They are a characteristic feature of the arid type of sedimentation. The constituents of these deposits are those that occur in the sea and in the waters of salt lakes, and they have evidently originated by the evaporation of masses of salt water which have by some means become isolated during a period of high temperature. Some of these salt beds, obviously of marine origin, are of great thickness, and since sea-water contains only about 3 per cent. of salts, they must represent the residue of an enormous volume of water. However, recent work on salt domes and salt plugs (see Chapter X) has given reason to believe that some of the vast masses of salt recorded in borings have been locally thickened by tectonic processes and do not imply the existence of widely extended beds of such magnitude. But even on more moderate estimates of thickness it is obvious that the volume of water required could not be supplied by a simple closed basin of any reasonable size, and the process could only take place on a sufficient scale in a locality where a supply of sea-water is kept up to make good the loss by evaporation. These conditions are well realised in the Kara Boghaz, a curious almost circular gulf on the eastern side of the Caspian Sea. The strait connecting the basin with the sea is only a few hundred yards wide and very shallow, while there is strong evaporation and little or no access of fresh water. A current of several miles an hour runs into the gulf and the strait is too shallow to allow of a low-level return current. Hence the water of the gulf is a highly concentrated solution and its floor is covered by a thick layer of rock salt.

When normal sea-water is being concentrated by evaporation

gypsum or anhydrite begins to precipitate when 37 per cent. of the water has been evaporated, whilst when 93 per cent. of the water has been removed it becomes saturated for rock salt. To bring down the more soluble magnesium and potassium salts 98 per cent. of the water must be removed. In very many cases desiccation has been incomplete, and calcium sulphate, either alone or accompanied by sodium chloride, is found. This is the case in Britain, where gypsum is common in the Trias, and salt is found in the Keuper of Cheshire and Worcestershire; at Middlesborough, probably in the Bunter, and at Carrickfergus near Belfast.

The most interesting case of apparently complete desiccation is

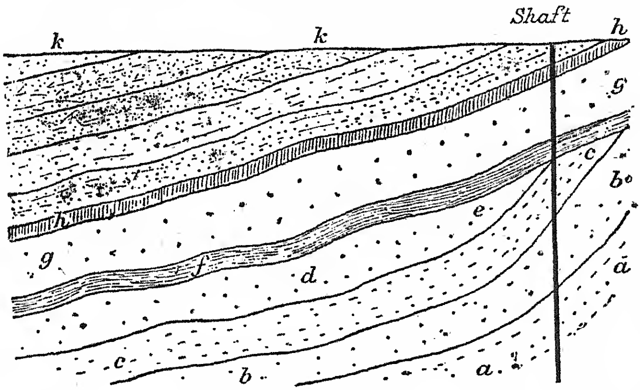


FIG. 67.—THE STASSFURT DEPOSITS.

a, rock-salt; *b*, polyhalite region; *c*, kieserite region; *d*, carnallite region; *e*, kainite region; *f*, impervious clay; *g*, anhydrite; *h*, gypsum; *k*, sandstone.

afforded by the Permian salt-beds of Stassfurt, in Central Germany, where in addition to the usual rock-salt and gypsum there are also numerous compounds of potassium and magnesium, often in the form of complex double sulphates and chlorides. A very elaborate experimental investigation by Van't Hoff and his pupils has established the order in which the different salts ought to crystallise out from mixed solutions containing the constituents of sea-water, and on the whole the arrangement of the Stassfurt salts agrees with their results.

The most important of the salts found are the following: epsomite, $MgSO_4 . 7H_2O$; carnallite, $KCl . MgCl_2 . 6H_2O$; kieserite, $MgSO_4 . H_2O$; polyhalite, $2CaSO_4 . MgSO_4 . K_2SO_4 . 2H_2O$; leonite, $MgSO_4 . K_2SO_4 . 4H_2O$; kainite, $MgSO_4 . KCl . 3H_2O$; sylvite, KCl; and the iodides and bromides of potassium and other bases. Boracite also occurs.

Fig. 67 shows a diagrammatic section of the principal deposit. The lowest bed reached consists of rock-salt with layers of anhydrite, $CaSO_4$. In the upper part this is mixed with kieserite and kainite,

and then comes a layer of carnallite. This is covered, with apparent unconformity, by a layer of impervious clay followed by a great thickness of anhydrite and gypsum. Above this are the sandstones of the Trias. The preservation of these highly soluble salts is due to the layer of clay above them, which protects them from percolating water. These salt beds are of very great commercial importance, and they are now the principal source of potassium and magnesium compounds, and also of iodine and bromine. The latter are obtained as by-products in the purification of the other salts.

Nitrates.—Deposits of nitrates are not abundant and indeed can only occur under exceptional conditions, owing to their high degree of solubility. Potassium nitrate is found as an incrustation on the soil in certain dry districts in India and elsewhere. It is deposited by evaporation of saline solutions brought to the surface by capillarity. On a much larger scale are the beds of nitrate of soda mixed with other salts found in the rainless district of Peru, in the desert of Atacama, and these are of great commercial importance. The deposits of crude nitrate, called Caliche, are found up to a height of 5,000 feet above sea-level, and as much as forty-five miles inland. The nitrate of soda is associated with sulphates, chlorides and iodides of potassium, sodium, magnesium and calcium, and also salts of boric acid. Two explanations of their origin have been widely put forward. According to one theory, they are weathered masses of animal bodies and excrement like the guano of Peru. Against this idea are the facts that they contain no phosphoric acid, and much iodine is present. The other theory traces their origin to masses of sea-weed, stranded by emergence of the land, and decomposed, giving rise first to ammonia compounds, and these, when acted on by bacteria, form nitric acid; this forms calcium nitrate, which in its turn interacts with sodium sulphate, yielding sodium nitrate and gypsum.

Siliceous Sinter.—In certain regions of expiring volcanic activity there exist hot springs whose waters are rich in dissolved silica, and these give rise to large deposits of the material known as siliceous sinter. The conditions governing the stability of a solution of silica are imperfectly known, but it appears that the separation of silica in the solid form from hot springs is due to several causes, viz. relief of pressure, cooling, chemical reaction, evaporation and plant life. The first four tend to produce a supersaturated solution, and thus to cause separation of solid silica. But certain algae, which live in hot water, are able to extract silica from solutions which are by no means saturated, and to deposit it in their tissues in the colloidal form. This gives rise to a layer of jelly-like material on the surface of the surrounding rocks, and when the plant dies the jelly solidifies to a porous or compact stony mass, either white or coloured by various metallic oxides. The best-known deposits of siliceous sinter are those surrounding the geysers

and hot springs of Iceland, the Yellowstone Park and New Zealand. They often assume very striking and beautiful forms, as in the case of the celebrated Pink and White Terraces of New Zealand, destroyed by the eruption of Tarawera in 1886.

Chert and Flint.—Many limestones of various ages have undergone more or less completely a process of *silicification*, in which the calcium carbonate has been replaced by silica in the chalcedonic form. The change appears to have been in most cases molecular, since the minute structures of the rock are often very perfectly preserved. Such a rock is called *chert*. Excellent examples of this process are found in the Upper Jurassic rocks of the Isle of Portland. In both the Lower and Upper Greensands of the south of England there are found beds a few inches thick almost wholly composed of chalcedonic silica, and associated with these are other beds rich in remains of sponges, originally siliceous, which have either been replaced by calcite or glauconite, or are represented by empty moulds. It appears that the silica of the sponge spicules has been dissolved away and redeposited as chalcedony in particular strata. Very similar cherts also occur in the Lower Carboniferous rocks of West Yorkshire, North Wales and Ireland, also associated with sponge spicules.

The Chalk of southern and eastern England contains many nodular and shapeless masses of black or grey chalcedonic silica, called *flint*. The origin of these has long been a matter of dispute, but it seems probable that they were formed in a manner essentially the same as that described above in the case of chert. Flints usually occur in lines and bands along the bedding or joints of the Chalk, and sometimes form thin layers continuous over a considerable distance. They often enclose fossils, especially sponges; when examined microscopically sponge spicules are seen to be abundant. Prof. Sollas's explanation of the origin of flint is as follows.[1] The sponge spicules in Chalk consist of opal, $SiO_2.nH_2O$, which is much more soluble than crystalline silica. It is either replaced by calcite or dissolved away completely, leaving hollow cavities. This dissolved silica is again deposited around siliceous patches in the Chalk, in the chalcedonic form. Thus the formation of flints is to be ascribed to a form of concretionary action. It is not known when the process occurred, but it appears to be at any rate posterior to the jointing of the Chalk.

Siliceous Oozes.—Reference has already been made to the radiolarian and diatom oozes at present being formed on the floor of the ocean far from land, and it was shown that deposits largely composed of radiolaria are characteristic of great depths. It is an interesting question to what extent similar deposits can be traced among the older rocks; and so far as is at present known they are rare. Cherts largely made up of the tests of radiolaria have been described from the Lower

[1] Sollas, *Age of the Earth*, p. 133.

Carboniferous rocks of North Devon, from Mullion Island off the coast of Cornwall, and from the Arenig rocks of the southern uplands of Scotland. These are fine-grained flinty-looking rocks commonly spoken of as radiolarian cherts. Their true nature cannot be regarded as established beyond all doubt owing to the bad preservation of the organisms. The best-established case of deep-sea siliceous deposits of this kind is in the islandof Barbados, where there are to be seen, at a height of 800 or 900 feet above sea-level, thick beds of siliceous rocks largely composed of radiolaria, and in association with strata closely resembling modern abysmal red clays. There have also been found in this series remains of echinoids of deep-water type. Beds of very similar character are also found in Trinidad and other West Indian islands. It is concluded that this region must have undergone an elevation of many thousands of feet in comparatively recent times, probably since the Pliocene.

It is now known, however, that some rock-types rich in radiolaria were formed in quite shallow water, such as the phthanites of Brittany and some Devonian or Carboniferous strata in New South Wales, which last are said to be 9,000 feet thick. The presence of radiolaria is not, as formerly thought, a proof of deposition at great depths, but of extra abundance of silica in water of any depth.

In many fresh-water lakes, especially in regions either now or formerly glaciated, there are found siliceous deposits mainly composed of diatoms (diatomaceous earth or Kieselguhr). Examples are found in the basin of a dried-up lake at Kentmere in Westmorland and in several places in the Highlands and Western Isles of Scotland. Others are known as far back as the Jurassic, and when consolidated are called *diatomite.*

Phosphatic Deposits.—The natural compounds of phosphorus are of great commercial importance, chiefly in view of their value in agriculture. The mineral apatite, which consists of calcium phosphate together with calcium chloride or fluoride, is found in some parts of the world to a considerable extent, especially in Norway and Canada. This mineral, however, chiefly occurs in the igneous and metamorphic rocks, and cannot be further described here. However, phosphatic accumulations of sedimentary origin are also widespread, and of great importance, both scientific and commercial.

Phosphorus is an important constituent of living animal tissue, and most phosphatic deposits can be traced directly or indirectly to this source. In certain rainless districts, especially on the west coast of South America and South-west Africa, there are found immense deposits of *guano*, which is composed almost entirely of the excrement and remains of sea-birds. It consists to a very large extent of nitrogenous and phosphatic substances, and is a most valuable manure.

In some cases beds of guano have caused a remarkable alteration

of the underlying rocks. A good instance of this occurs in Christmas Island in the Indian Ocean, where some of the raised reef-limestones have been more or less completely converted into calcium phosphate. Another interesting case is that of Clipperton Atoll in the eastern Pacific, where a trachyte has been phosphatised to a varying extent in different parts of the mass, so that although the typical trachyte structure is still discernible, 95 per cent. of the rock consists of phosphates of iron and alumina. In this case it is supposed that ammonium phosphate derived from guano has replaced the silica and alkalis of the felspar. The phosphorite or redondite of Redonda, in the West Indies, similarly shows the structure of an andesite, but consists of phosphates of iron and alumina.

In many sedimentary deposits, and especially in those of shallow-water origin, there are found nodular masses of phosphate of lime. Many of these are obviously the fossilised excreta of animals, while others are recognisable fossils, and others again are mere lumps of calcareous mud which have been changed into phosphate. Such phosphatic nodules are commonly and commercially known as *coprolites*, though strictly speaking this term should be confined to fossilised excreta. One of the best-known examples is the so-called Cambridge Greensand (for further description of this see Chap. XXIII). Such phosphatic nodule-beds are specially characteristic of what is known as pene-contemporaneous erosion, where strata have been removed by wave-action and currents soon after formation. The presence of the phosphate is probably accounted for by the abundance of life in shallow waters. In the modern seas, deposits containing phosphates and glauconite are now being formed in certain localities, very similar to the Greensands of the Cretaceous. Some modern deep-sea deposits also strongly resemble the phosphatic Chalk of the south of England, France and Belgium. In most of these cases it appears that phosphorus compounds of organic origin have reacted with calcium carbonate to form calcium phosphate. This process of phosphatisation may be reckoned among the metasomatic changes undergone by calcareous rocks.

Carbonaceous Rocks.—Under this heading are included all those ancient and modern sedimentary deposits in which the most important constituent is carbon (rocks consisting chiefly of carbonates are excluded). From the practical and commercial point of view some of these are about the most important of all the known constituents of the earth's crust. As a matter of convenience, there are described here also certain carbonaceous substances found within the earth's crust which are certainly not rocks in the ordinary sense of the term, and are not even solid. Such are rock-oil (petroleum) and natural gas. These, however, closely resemble some of the carbonaceous rocks in chemical composition, and are naturally classed with them.

Coals.—At almost all times from the Devonian upwards there have been formed in some parts of the world great accumulations of vegetable matter. These have later undergone more or less completely a peculiar kind of decomposition, eventually forming substances of a bituminous nature: the most important of these products is *coal.* The origin of such deposits has given rise to a good deal of discussion, but it is now generally agreed that the great majority of the carbonaceous rocks are of fresh-water or terrestrial origin, only a few special types being marine. The first group originated as peat, or something very like it: this type is characterised by the presence of a large proportion of woody material, and when more or less altered in course of time gives rise to the important group of the humic coals. The non-woody or sapropelic group is of much less importance, and consideration of it may be postponed for a while. In general terms, starting from peat as the primary material, the process of formation of the other members of the humic group may be summarized as an increase of the carbon content with corresponding elimination of other constituents, jointly proportional to age and depth of burial. The simplest method of treatment is to begin with the modern representatives.

Peat.—At the present time there are found in many parts of the world great deposits of more or less decomposed vegetable matter of varying character, to which the general term of *peat* is commonly applied. The greatest developments of peat are seen in temperate and cold regions, where the climatic conditions seem to be most favourable to its formation. It is rare in the tropics, while the greatest peat-bogs of the world occur in the arctic portions of Asia and North America, the Tundras, where the subsoil is permanently frozen throughout the year and the surface vegetation consists chiefly of mosses. Peat occurs to a considerable extent in the British Isles, and here it is possible to recognise two distinct types of slightly different composition—Hill-peat and Fen-peat.

Hill-peat consists very largely of the remains of *Sphagnum* and other mosses, and is usually a brownish or nearly black fibrous, spongy substance in which the vegetable structure is still clearly visible. It often encloses numerous trunks and branches of trees, such as the well-known bog oak of Ireland. It is usually found at fairly high elevations, especially in the widely spreading moors of the north of England and Scotland, but in the west of Scotland and in Ireland it is also seen at lower levels.

Fen-peat is commonly a darker-coloured and more muddy deposit, consisting largely of the remains of rushes, sedges and other water-plants. It is found at low elevations, such as the Fenland of Eastern England and the so-called 'moors' of Somerset (Sedgemoor, etc.). Buried forests are common, and frequently occur at definite levels, probably indicating variations of climate or periods of more effective

drainage. Near Ely five such forests have been traced, and a similar succession is known among the peat-bogs of Denmark.

The depth to which peat has accumulated in British peat-bogs is very variable: it rarely exceeds 50 feet, and is usually much less. Much attention has been paid to the character of the plants composing the peat, and it has been found that the constituents of the lower layers of many of the Scotch and English peat-bogs indicate that they were formed during the later stages of the Glacial period, and a definite succession can frequently be made out.[1] The growth of peat is evidently a very slow process, and in many localities appears to be stationary at the present time, while in other places it is certainly being destroyed by denudation. The process of its formation is evidently a peculiar limited decomposition of vegetable matter while saturated by water, so that oxidation is in abeyance, and it is probably brought about largely by bacteria.

Lignite and Brown Coal.—These terms are used by different writers in somewhat different senses in Britain, Germany and America. At any rate, the deposits here included form a continuous series in the progression from peat to coal. Most of the material usually called lignite may be regarded as peat of ancient date, chiefly Tertiary, but still retaining a good deal of its original character, though buried under later deposits, and not now in process of formation. Lignite is rare in Britain, the only important occurrence being in a Tertiary lake basin near Bovey Tracy in Devonshire, where it is interstratified with beds of china clay derived from Dartmoor. This and many foreign examples of lignite seem to have been formed under more or less tropical conditions, as shown by the character of the plant remains.

Brown Coal in the usual German sense is not found in Britain. The group includes varieties ranging from what is really the same as some lignites to the sub-bituminous coals of the British and American nomenclature: all varieties agree in having a brownish streak. Many of the seams are very thick and the group is of great economic importance in Germany.

Sub-bituminous Coals.—In the Mesozoic and Tertiary formations of the Rocky Mountain region there are thick seams of what in America is called sub-bituminous coal: this is softer than ordinary house coal, with a higher water content. In Britain this type is only found as a few thin seams in the unfortunately named 'Estuarine Series' of the Middle Jurassic in Yorkshire, which is a typical coal-delta on a small scale.

Bituminous Coal.—This group includes the ordinary household and coking coals, which scarcely need description. Much work has been done on the nature of the various constituents of coal, but details cannot be given here, especially as some of the technical terms employed are

[1] Lewis, *Proc. Roy. Soc. Edin.*, 1907.

used in varying senses by different writers. It must suffice to say that coal consists almost entirely of vegetable matter of many kinds in an advanced state of alteration, with a high concentration of carbon. It is clear that the bituminous coals are fresh-water delta deposits, probably formed for the most part during pauses in the depression of a sinking area. Each seam is usually underlain by a seat earth or fire clay, representing the soil in which the coal plants grew. In most coalfields there are occasional marine bands, often of wide extent and useful in correlation of coal-bearing strata in detached areas. Fresh-water mollusca and plants are also used in zoning. All the British coals of this class are of Upper Carboniferous age and further details will be found in the chapter on that system.

Steam Coal.—This type, which is intermediate between house coal and anthracite is sometimes called semi-bituminous, but this is liable to confusion with the sub-bituminous group before mentioned. It is a hard brittle coal with a prismatic fracture. It burns with a smokeless flame and very high heating value.

Anthracite.—This is the form of coal with the highest carbon concentration. It has a sub-metallic lustre and conchoidal fracture: it burns with little flame and no smoke, and is clean to handle owing to the absence of the soft black material so characteristic of house coal. Its heating value is very high, but it is difficult to burn in some types of open grate.

Jet is a substance closely allied to coal: it occurs in isolated masses sporadically distributed throughout 10 feet of black shale in the *exaratum* zone of the Upper Lias of Yorkshire. Each lenticle is an individual altered wood fragment, greatly compacted and now homogeneous, of a dense black colour and capable of taking a high polish. A poorer quality of jet is found in the clays of the 'Estuarine Series' above.

Rank of Coal.—The varieties of humic coals have here been described in a definite order, depending on carbon content and other correlated characters. The position of any variety of coal in this series is spoken of as its *rank*, peat being the lowest and anthracite the highest. As before mentioned, the rank of a coal depends partly on age and partly on depth of burial. Some anthracites might almost be regarded as metamorphic rocks.

Graphitic Rocks.—In some Precambrian and metamorphic areas there are found masses of graphite. The origin of some of these, especially of those occurring, as in Ceylon, in vein-like masses, is uncertain, but graphite is common in many crystalline schists which undoubtedly were originally sediments: in some cases as in the Precambrian of Canada and South Australia the graphite may be due to reduction by metamorphism of the carbonates of limestones or dolomites. But other occurrences, as, for example, in certain places in the eastern Alps,

were certainly once coal-seams, as they can be traced into less highly metamorphosed regions where they are associated with Carboniferous plant-remains. Some of the deposits are said to consist of amorphous carbon and not true crystalline graphite. Some graphitic beds may have originally been oil-shales rather than coal.

The Sapropelic Coals.—In some fresh-water lakes and in shallow pools in swampy districts there are found masses of much decomposed carbonaceous matter, some of which at any rate consists largely of unicellular oil-bearing algae. This kind of material is called *sapropel*, and some ancient coals were probably formed in the same way. The most important of these are *cannel coal* and *boghead* or *torbanite*. These show little or no vegetable structure except under special treatment, when they are found to consist largely of spores of lycopods and what appear to be cells of algae.

Cannel coal is dull black and breaks with a conchoidal fracture: it burns with a smoky flame like a candle and yields much gas. The Scottish boghead coal is very similar to this and is also closely allied to the oil-shales.

Petroleum and Allied Hydrocarbons.—Naturally only the merest outline of the subject of petroleum and oil geology can be given here. There is now a vast and highly specialised literature on the subject, but a few of the more generalised works are quoted below.[1]

In many parts of the world the sedimentary strata are characterised by containing vast quantities of free hydrocarbons in the solid, liquid or gaseous state of which petroleum, the liquid form, is the most important economically. Under this term are comprised a varied and complex series of liquid hydrocarbons which, while mainly of the paraffin series, contain varying amounts of compounds of the aromatic series. Petroleum of very similar composition is also obtained by the destructive distillation of the bituminous or oil shales found in certain areas. The true oil or 'kerogen' shale contains little or no free petroleum until the kerogen is decomposed in the retorting process. Closely allied to, and often associated with, petroleum are the gaseous hydrocarbons or 'natural' gas, consisting mainly of the lowest members of the paraffin series. The solid hydrocarbons vary considerably in type: pitch and asphalt are terms somewhat loosely used to describe the impure oxidised semi-solid residue resulting from the natural evaporation of certain types of oil. Distinct from these are the natural bitumens that occur as intrusive veins in non-bituminous strata. Those originating from asphaltic oils are usually black glistening substances with fractures and properties that depend on their composition; a natural light-

[1] A. Beeby Thompson, *Oilfield Exploration and Development*. Crosby Lockwood & Son, 1925; E. R. Lilley, *The Geology of Petroleum and Natural Gas*. Chapman & Hall Ltd., 1928; W. H. Emmons, *Geology of Petroleum*. McGraw-Hill Publishing Co. Ltd., 1931.

coloured wax derived from oils rich in solid paraffins is known as ozokerite, and is similarly found in veins and slip planes.

Distribution.—Petroleum and these allied hydrocarbons are no freak constituents of the earth's crust, but are very widely distributed stratigraphically, geographically and in depth; from the Cambrian upwards all the geological systems have indications of oil in some part of the world. Important production of oil from the Palaeozoic is so far confined to North America, and apart from this the Tertiary formations are by far the most important as oil producers. Geographically the distribution is just as wide and practically no country is without some trace of oil, though often not in amounts capable of economic development. As regards depth of occurrence no limit has yet been found and in a well completed in 1938 in California at a depth of 15,004 feet oil is being obtained from the Miocene at a depth of over 13,000 feet. Of those regions which have produced or are producing the bulk of the world's oil supply, the most famous are Pennsylvania, California, Oklahoma, Louisiana and Texas in the U.S.A., Russia, Roumania, Poland, Mexico, Peru, Trinidad, Burma, Iran, Iraq and the East Indies.

In Great Britain oil has long been known to exist here and there in the Carboniferous, and in 1913 a boring put down for coal at Kelham, Notts, struck a thin oil sand. Towards the close of the Great War several wells were drilled to test the possibilities of commercial production in the Carboniferous. Of these only one, at Hardstoft in Derbyshire, has produced oil in any quantity. Oil was struck at the top of the Carboniferous Limestone at a depth of about 3,000 feet, and has produced to date about 20,000 barrels. Another test at Darcy in Midlothian struck an oil sand in the oil shale group and yielded a few barrels of oil.

Recently a much more active and widespread programme of exploration has been in progress, but so far without result, apart from proving a considerable natural gas field just south of Dalkeith in Midlothian.

Oil shales are also of wide occurrence: they are found in the Lower Carboniferous of Scotland, the Jurassic shales of Kimmeridge and Norfolk: they are also found in Canada, U.S.A., Esthonia, Spain and Australia. It is only in Scotland and Esthonia, however, that so far they have been successfully developed. Natural gas, though usually closely associated with petroleum, may sometimes occur alone. The U.S.A. provide many examples of wells giving huge quantities of gas only, while in this country it is often met with in the Coal Measures, and near Heathfield station in Sussex a boring for water in the Wealden and Purbeck beds in 1896 tapped a supply of gas which continued for many years.

Asphalts and bitumens generally occur closely associated with the heavier types of oil and one of the most remarkable occurrences of

asphalt in the world is in Trinidad, where it forms a lake half a mile in diameter.

Origin of Petroleum.—On this subject there is still much controversy and a vast literature. The old inorganic theory of derivation from carbides and water has practically been discarded and the natural distilling of petroleum from oil shales by the intrusion of igneous rocks, while undoubtedly occurring sometimes on a considerable scale, probably represents a very small part of petroleum deposits as a whole. Modern theories are undoubtedly converging on natural petroleum having been formed by the decomposition of organic matter, mainly marine organisms, under suitable conditions. There is considerable evidence that an important and probably essential factor is the existence of 'euxinic' conditions such as are known to exist in the deeper parts of the Black Sea. Under such conditions owing to lack of oxygen or presence of sulphuretted hydrogen there is an absence of sea-floor life, so that dead organic matter from nearer the surface can accumulate along with the sedimentary deposits. Many such muds have been examined and show the presence of petroleum-like hydrocarbons.

Mode of Occurrence.—Oil is found saturating many types of rock, shales, sandstones and limestones. In some cases oil has undoubtedly been formed in the beds where it occurs, but, being a liquid and subject to hydrostatic laws, it tends to 'migrate' and accumulate in the more porous rocks, especially if these are over- and under-lain by impervious strata. If these porous beds were already charged with water, the oil, being of lower specific gravity, will rise into the anticlines, the actual crest often being occupied by gas. In such circumstances the oil may be under high hydrostatic or gas pressure, giving rise to gushing wells of varying intensity when the covering strata are pierced. Where oil-bearing beds outcrop at the surface, or where, owing to a fault, dyke, or other circumstance, there is communication between the surface and lower beds containing oil under pressure, its presence may be revealed by 'seepages' or natural oil springs, mud volcanoes, gas issues, or asphalt deposits.

Mud Volcanoes.—While mud volcanoes are a well-known geological phenomenon it is not easy to decide whether they should be discussed under 'Vulcanicity' or 'Oil Indications.' They necessitate outbursts of natural gas through shale or clay formations, and as this combination is much more frequently met with in association with hydrocarbon accumulations than true vulcanicity they perhaps belong more strictly to 'oil geology.' The typical mud volcanoes as, for example, those of Trinidad, Burma, Baku, etc., are essentially oilfield phenomena. In either case they are due to natural gas under pressure finding its way up along faults or other planes of weakness through clay formations in presence of water. The high pressure gas forms the motive power which brings to the surface a thick or thin mud according to circum-

stances and this gradually builds up a mud cone often with a well-marked 'crater' in the centre. These cones may be of considerable size, some of the Russian ones being up to 250 feet in height. Many mud volcanoes show on a small scale the intermittent characteristics of the Vesuvian type of true volcanoes. They may be dormant for relatively long periods while the sub-surface gas pressure is building up; a violent eruptive period may then occur during which the cone is still further enlarged and the material ejected may contain fragments from formations far below the surface. This type of mud volcano may occur below sea-level and where the sea is shallow may even give rise to islands: these may emerge suddenly, but owing to the soft nature of the materials they disappear almost as quickly owing to wave action. Such temporary islands have been recorded in the Gulf of Paria off the coast of Trinidad, the Klias Peninsula of Borneo and the Arakan Islands.

In certain oilfields, formations now far below the present surface have been identified as the mud flows from earlier mud volcanoes.

Somewhat similar phenomena may be associated with the later phases of true volcanic action where ejections of hot water and solfataric gases may break through clay formations and bring mud to the surface forming very similar mud volcanoes. Of this type the mud volcanoes of Paterno in Sicily are of special interest because they occur along the line of the great fissure which runs in a S.S.W.–N.N.E. direction through Etna and the Lipari Group. Although mud volcanoes formed by either of these two methods may be similar they should be clearly differentiated from the standpoint of geological history: the one type is a product of the dying phase of true vulcanicity while the other and more frequent one is associated with the formation of hydrocarbon gases as normal constituents of certain sedimentary deposits and therefore quite distinct from true vulcanicity.

Concretions.—In many rocks of all classes there are to be found masses differing from the rest in composition or structure, or both, and possessing quite definite, though often very variable, forms. Many, though not all, of these have formed in the position where they now lie, either during or after formation or the consolidation of the rock. For want of a better name these are all classed together under the general heading of concretions, though some of them have certainly not been formed by what are generally understood as concretionary processes. Such concretions are often more or less spherical in shape, also spheroidal or lenticular; sometimes nodular or botryoidal, or possessing many other forms. Some are scattered at random through the rock, while others are found only in more or less regular layers. Sometimes they lie so close in a particular stratum as to coalesce into a nearly continuous bed, and in such an instance they may be rectangular in form.

The nodular structures found in the igneous rocks are not of much importance or interest. Certain granites and diorites show a regular radial and concentric arrangement of their minerals, often with layers of dark and light minerals alternately, as seen in the orbicular granites of Scandinavia and the orbicular diorite of Corsica. This structure is due to rhythmic super-saturation and precipitation in a crystallising magma, as shown by Liesegang.[1] Some rhyolites and other lavas, again, show a nodular or lumpy structure probably produced during the change from a glassy to a crystalline condition (devitrification). The so-called orbicular or spheroidal weathering of many igneous rocks is quite a different process, and the resulting rounded masses must not be confused with concretions: they are due to decomposition, not to growth.

The concretions of the sedimentary rocks are much more common and characteristic. They may occur in rocks of almost any kind, and are obviously formed in many different ways. Some are clearly formed during the deposition of the rock, while others are as certainly of secondary origin. There are also instances of doubtful relative age.

Perhaps the commonest of all concretions are the more or less spherical or ellipsoidal calcareous or ferruginous nodules so common in many clays and shales. In some parts of the country these are called *doggers*, especially when ferruginous. They are found in argillaceous rocks of almost all ages, and only a few examples can be mentioned; they are specially common in the Wenlock Shale, the Coal Measures, the Lias, and the Kimmeridge Clay. In the latter, as at Ely, they may be a yard across; from 6 inches to 1 foot is a very common size. In the lowest bed of the Middle Jurassic of Yorkshire this type of structure is so conspicuous that the word Dogger is used as a stratigraphical name. The calcareous nodules of the Lias have been largely used for making Portland cement, while the ironstone nodules of the Coal Measures and of the Lias are in some cases valuable ores. When broken open they are often found to contain fossils, and frequently show what is called septarian structure, with a central cavity and more or less radial cracks, which taper outwards and do not reach the surface. These cracks often get filled up by calcite, iron carbonate, or even zincblende and galena. In certain cases, where a formation consists of an alternation of thin limestone bands separated by thicker layers of clay or shale, it has been suggested that the limestone bands may really be of concretionary nature, the calcium carbonate, at first spread almost uniformly throughout the rock, having been dissolved and reprecipitated along certain bedding planes, or the lime may have been brought in in solution and rhythmically precipitated within the clay. Very closely related to these calcareous

[1] Liesegang, *Geologische Diffusionen*, 1913.

and ferruginous concretions are the flints of the Chalk, whose character and supposed origin is described on p. 177.

Some of the most striking concretionary forms known are those of the Magnesian Limestone in Durham, which have been well described by Professor Garwood.[1] These have most extraordinary shapes, such as botryoidal, reniform, dendroid, basket-like, and many forms which can only be described as fantastic, some closely imitating various organic structures such as sponges and corals. Professor Garwood showed that the concretions consist mainly of calcite, while the rest of the rock is highly dolomitic, and he concludes that they were formed by crystallisation of the original calcium carbonate of the limestone around fossils and other nuclei, some of which have since disappeared, leaving central hollows. Such concretions only seem to form in dolomitic strata, and are absent from beds in the same series which do not contain magnesia.

Many sandstones and ironstones show structures commonly known as *box-stones*; these are in a certain sense the inverse of concretions, since the movement of the material seems to have been outwards, at any rate in part. Typical box-stones, such as are seen in the Lower Greensand, are spheroidal or more commonly more or less rectangular, generally hollow, sometimes empty, but usually partly filled with loose bleached sand. The walls consist of hard iron hydroxide cementing sand grains and are usually about half an inch thick. The deposition of the iron in these hard shells is probably determined by joints, as it is very similar to the coatings of iron hydroxide so often found around natural joint blocks of sandstone, as in the Carstone at Hunstanton and in many Jurassic sandstones in Yorkshire.

Another common type of concretion takes the form of radiate spherical or nodular masses of iron sulphide, often marcasite, sometimes pyrite, so often found in the Chalk. Many of the metallic and other minerals found in mineral veins and other ore deposits possess a concentric or radial structure or both, very like that of typical concretions, such as the well-known kidney-ore (haematite) of Cumberland and the very similar botryoidal masses of limonite and various manganese minerals, and the concretionary lumps of bright green malachite in the oxidised parts of copper lodes. This type of structure is believed to be due to deposition from colloidal suspensions and is often spoken of as *colloform*.

A puzzling type of structure is that known as *cone-in-cone*, where masses of calcite or less commonly other minerals of apparently concretionary origin are made up of numbers of conical or pyramidal pieces fitting one into the other, and building up a continuous stratum. This structure is apparently due to a peculiar type of crystallisation, and may also be due to colloidal suspensions percolating through the solid rock, and precipitated in layers of favourable constitution.

[1] *Geol. Mag.*, 1891, p. 433.

CHAPTER X

EARTH MOVEMENTS

Instability of the Earth's Crust.—There is abundant evidence that the crust of the Earth is structurally in a state of unstable equilibrium. As has been pointed out in the introductory chapter, strata originally horizontal are now found to be tilted, folded, faulted and otherwise disturbed; in fact, it is exceptional for this not to be the case. Besides this evidence of movement in the past, the occurrence of earthquakes and other observable disturbances at the present day shows that the same processes are still in operation. As a matter of convenience, crust movements may be considered under two headings—*rapid* and *slow*—although the difference between them is only in degree, not in kind. Rapid movements produce sudden and violent changes in a short period, while slow movements are usually only to be discerned by the effects produced after a long lapse of time.

Rapid Movements.—Observation by means of sensitive instruments has shown that the crust is in many parts of the world in a state of almost constant vibration, and that there exists every gradation between these minute tremors and the conspicuous disturbances called earthquakes. Even in our own country, commonly regarded as very stable, these tremors can be detected. In Perthshire, near the Grampian fault, they are of constant occurrence, and about 100 years ago earth-shakes of measurable intensity sometimes occurred in this region at the rate of two or three a day, though they are much less frequent now. Since this highly unstable stretch of country lies alongside one of the greatest faults in the British Isles, the connexion is obvious.[1]

Earthquakes.—Tremors and sudden disturbances powerful enough to be sensible without the aid of instruments are popularly known as earthquakes. It is evident, however, that no hard and fast line can be drawn between these and the slight tremors described in the last section; the difference is in degree only. Earthquakes can be conveniently divided into two classes: (1) those of volcanic origin and (2) those due to crust movements unaccompanied by vulcanicity. These two classes differ to a certain extent in character as well as in origin. The study of earthquakes is of great importance in geology, since in the hands of physicists and mathematicians it has yielded much

[1] Davison, *History of British Earthquakes*. Cambridge, 1924.

information as to the nature of the earth's interior. However, it is not possible here to describe how this is done.

Earthquakes of Volcanic Origin.—The eruptions of volcanoes are generally accompanied by disturbances of the ground in their neighbourhood, and in volcanic districts shocks often occur unaccompanied by any eruption. These are in most cases undoubtedly due to the volcanic activity, and very often such a shock may be regarded as an unsuccessful attempt at an eruption. An excellent example of an earthquake of volcanic origin is afforded by that which destroyed the town of Casamicciola, in the island of Ischia, in 1883. Although the whole town was laid in ruins, and nearly 2,000 lives were lost, the shock was scarcely felt at Naples, only twenty miles distant. The smallness of the area of great destruction in this and similar cases is to be accounted for in two ways: partly by the slight depth at which such shocks originate, and partly by the smallness of the total energy involved.

Dislocation Earthquakes.—Of far greater importance than the foregoing class are the shocks due to actual movements of parts of the earth's crust. These are to be regarded as subsidiary phenomena accompanying the slow massive movements which will be dealt with in a subsequent section. In fact, earthquakes form the most important part of the evidence for the occurrence of such movements at the present time. The shocks of this class are now considered to be due to sudden slipping of the walls of a dislocation, such as a fault or thrust plane. The walls of such dislocation planes are rough and the friction is great, so that when a slip does occur a sudden jar is communicated to the surrounding rocks. It appears that the actual amount of slipping needed to produce a considerable shock is very small, usually only a fraction of an inch. In some cases, however, relative displacements measurable by feet have been suddenly brought about during earthquake-shocks, as in Japan in 1891 and in Assam in 1897, where the visible relative displacements amounted to about 20 and 30 feet respectively. Earthquakes of this kind are specially notable, in contrast to volcanic quakes, for the great extent of country over which they can be felt. They are also always accompanied by what are known as *after-shocks*, a series of tremors of gradually decreasing intensity, which sometimes continue for days, weeks or even months. They are caused by the gradual settling down into a state of equilibrium of the disturbed blocks, and rarely or never occur after volcanic quakes. Minor earthquakes are also caused in certain regions by the falling in of caves, and some of the local disturbances in certain parts of this country, reported as earthquakes in the popular press, are due to the collapse of disused mines.

Nature of Earthquakes.—An earthquake may be defined as a series of vibrations set up in the rocks of the crust by an impulse, or series of

impulses, originating at a greater or less depth below the surface. The exact nature of these vibrations or waves will be considered later in the light of recent results. The shock may originate at a point, or over a more or less extensive region; in volcanic quakes the origin is often very limited, approaching a point, but in dislocation quakes the origin is obviously in most cases a plane, which may be either vertical or inclined at any angle. From this origin, which is called the *focus*, the shock travels outwards in the form of waves, the surface of distribution being at any moment approximately a sphere, with the focus as a centre. Evidently, however, if the focus is linear the waves will not be spherical, but ellipsoidal. Such waves will obviously emerge on the surface as ellipses, and the intensity of the shock will vary inversely as the square of the distance from the focus, so that if we join on a map all the points at which the intensity is the same, we shall obtain a curve showing the form of the section of the wave-surface cut by the earth's surface. Such a curve is called an *iso-seismal line*; and diagrams of these lines have in many cases afforded important information about the relations of earthquakes to known tectonic features, and especially to faults, since the long axes of the ellipses are often found to be parallel to important lines of dislocation. On the other hand, when the long axis of such an ellipse is not parallel to any known dislocation, it is a fair inference that such exists below the surface, though concealed by overlying deposits. The intensity of the shock at any given point is also affected by other factors: as would naturally be expected, the waves are transmitted most freely by solid rocks, while their velocity is much reduced by loose material, such as sand, though the destructive effect is often very pronounced in regions covered by such deposits as alluvium and swamp soils.

Depth of Origin.—Many attempts have been made to determine the depth at which the shocks originate, but the methods hitherto employed are somewhat uncertain, owing to the doubtful accuracy of the data available. The oldest and simplest method depends on observations of the direction of cracks in buildings, on the assumption that these are at right angles to the direction of propagation of the waves. Lines are drawn at right angles to the cracks in buildings situated some distance apart, and the point of intersection of these perpendiculars is assumed to be the focus. This method gives fairly concordant results, usually ranging from five to twenty miles for the depth of the more important shocks. The results arrived at in other ways are in general accordance with this.

Earthquake Waves.—When a solid body is subjected to a sudden strain or shock, either of compression or torsion, vibrations are set up within it, which take the form of waves of various kinds. In solids two kinds of waves are possible: waves of compression and waves of distortion. In the former type, the particles move backwards and

forwards in the direction of their transmission: these may be called longitudinal waves. In waves of distortion, the particles vibrate in directions transverse to the direction of transmission. By means of modern instruments of precision it has been found possible to analyse earthquake waves, and it is found that both kinds of waves are always present; besides these, a third kind of wave consists of actual undulations of the superficial layers of the earth, of long period compared to the others. The different kinds of vibrations travel at different rates, so that when a record of a very distant shock is obtained the traces of the waves of each kind are clearly separated. It is found that the longitudinal waves have an average velocity of about five miles per second, while that of the transverse waves is about half this amount. At a great distance also the former are much less intense, and make themselves manifest as the 'preliminary tremors' which herald the arrival of the main shock in all great earthquakes. The main shock seems to be due to the joint action of the transverse waves and those of the third kind, the surface waves, which are propagated along the outer crust and therefore travel along the circumference of the spheroid. Waves of the other kinds travel through the earth, but not in straight lines, since they are refracted at the bounding surfaces of masses of rock of varying density; hence the velocities of the two kinds of waves are different, since they are unequally refracted and arrive at different points at different times.[1]

Geological Effects of Earthquakes.—Although the phenomena accompanying a great earthquake are such as to produce a great impression on the mind of man, their geological importance is usually considered to be but small. The actual changes brought about by them are generally quite insignificant, except in so far as they affect human handiwork. A very common accompaniment to important shocks is the formation of open cracks in the ground, especially in loose material, and from these cracks water, mud and sand are sometimes ejected: in mountainous regions important landslips often occur. In some cases there is good evidence of an actual change of level, with differential movement. Reference may be made to the visible faults produced during the Mino-Owari earthquake in Japan in 1891, and the Assam earthquake of 1897. In New Zealand, in the year 1855, an area as large as Yorkshire was permanently elevated several feet, and in 1897 part of the land bordering Disenchantment Bay, Alaska, was raised 47 feet. The classical instance of such a displacement is that described by Darwin in Chile in 1835, and there is good evidence to show that such a phenomenon has occurred again and again in that region,

[1] For a clear and concise account of the whole subject, including an explanation of the application of the study of earthquake waves to the problem of the nature of the earth's interior, see Davison, *A Manual of Seismology*, Cambridge University Press, 1921.

resulting in a total elevation of many hundreds of feet, since the advent of still-existing species of shells.[1]

Simple and Twin Earthquakes.—A comprehensive study of many recent shocks in Britain and elsewhere by Dr. Davison [2] has shown that they belong to two distinct types: in simple earthquakes there is only one principal shock, which is clearly due to slipping along a fault-line of the ordinary type, such as is formed by simple vertical displacement; in other cases the shock is double, consisting of two principal shocks with a short interval of time between them: the origin of this latter kind is rather obscure.

Submarine Earthquakes.—A good many earthquakes appear to originate beneath the sea, and these chiefly manifest themselves by the waves to which they give rise: these waves often cause tremendous damage and loss of life on the coasts of the neighbouring land. Their origin is apparently to be sought in an uplift or subsidence of the sea-floor. If the cause is a subsidence the sea retreats from the land before advancing, whereas in the case of an uplift the advancing wave is the first sign of disturbance. The great earthquake of Lisbon in 1755 seems to have been of submarine origin. It also appears that earthquakes may originate by the sliding of great masses of sediment down steep sub-oceanic slopes, such as frequently border the great continents. Such appears to be the cause of some of the earthquakes of the west coast of South America, and of some of those in the West Indies, e.g. Kingston, Jamaica.

Some Recent Earthquakes.—Within recent times many disastrous earthquakes have been recorded, and the supposed causes of some of them have already been mentioned. Of these, the Japanese shock of 1891 and the Indian one of 1897 were clearly due to movements along lines of dislocation, which were indeed clearly visible on the surface of the ground: to the same class belong the well-known quakes of Charleston in 1886 and Andalusia in 1884. More recent examples are the San Francisco earthquake of 1906, where also there was a measurable displacement on the surface, and the terribly destructive shock which destroyed the cities of Messina and Reggio on December 28, 1908. The Tokyo earthquake of September 1, 1923, one of the most destructive on record, was accompanied by great changes of level in the sea-floor. At one point there was an uplift of 135 fathoms, at another a depression of 259 fathoms. Since the sea wave was not very great, it is probable that these changes took place during the period of instability following the shock rather than during the earthquake itself.[2]

Slow Movements.—Although the rapid movements of the crust described in the preceding sections are the most obvious and striking

[1] *The Voyage of the Beagle*, Chapter XIV.
[2] Davison, *Great Earthquakes*. London, 1936.

in some of their effects, and indeed the only ones actually visible while in progress, yet they must be regarded as mere subsidiary incidents in a series of much greater phenomena. When a fracture is accompanied by relative displacement, it is only to be expected that this movement of displacement will occur intermittently, owing to friction between the rough fractured surfaces. These sudden slips give rise to earthquake shocks, and their sum-total, during the lapse of a long period of time, forms the greater movements which originate the leading structures of the visible part of the earth: these have led in innumerable cases to disturbances of extraordinary magnitude and complexity.

It is now the custom to divide earth-movements in general into two major categories, *epeirogenic* or continent-building, and *orogenic* or mountain-building. The main idea is that in the first class the forces producing the displacements act in a vertical direction, either upward or downward, while in orogenic movements the forces act primarily in a horizontal direction, tangential to the earth. It is obvious that tangential forces acting on an imperfectly rigid crust must induce compression or crumpling, or both, and that locally there will be vertical components in the resulting crust-movements, but the general principle holds, and there is doubtless a fundamental difference in the causes of the two kinds of crust-movement.

In recent years a great deal of light has been thrown on the structure of the earth in general and on the relations of its surface features by the study of the distribution of gravity, or perhaps it would be more correct to say, the distribution of mass. Determinations, mainly by means of pendulum observations or in submarines, of the value of the gravity-constant in different parts of the world have shown that on the whole there is a defect of mass on the continents, especially in great mountain-ranges, and an excess of mass in oceanic areas. This means essentially that the continents are composed of lighter rocks than the floor of the oceans. Thus in general the blocks of light rock stand up higher than the heavier ones, or, to put it in another way, it takes a higher column of lighter rock than of heavy rock to produce the condition of equilibrium, just as when two liquids of different densities are balanced against each other in a U-tube. This is the foundation of the doctrine of *isostatic compensation*, which regards the light continents as actually floating in a substratum of heavier rock; the substratum must on this theory be regarded as behaving in effect like a viscous liquid. There is, in fact, an analogy between the isostatic floating of the continental blocks and the floating of icebergs or floes in water. Further, if at any point there is an upward bulge, e.g. a mountain, on the light block, there must be a corresponding downward bulge at its base to balance it and preserve equilibrium.

It is evident that if the thickness, or weight, of such a floating block

is changed it must either rise or sink. If, therefore, a continent is reduced in thickness by denudation it will rise, and we shall see evidence of such rise in a retreat of the sea. If the weight is increased by formation of a continental ice-cap, or possibly by the pouring out of floods of basaltic lava, as in fissure eruptions, the continent will sink and drowned valleys will be found, marine deposits will extend over former land areas, or other evidences will be seen of a rise of sea-level relatively to the land. Such are the true causes of epeirogenic movements in accordance with the doctrine of isostasy: simple risings or sinkings of the land areas under the laws of hydrostatics.

It is sometimes supposed that continents may rise or sink as a result of forces inherent in the crust itself, but it is difficult to see how such can arise independently of bendings or warpings due to horizontal pressures, which would bring them within the category of orogenic movements.

Continental Drift.—Till early in the present century it was always tacitly assumed in geological discussions that the continents have remained rooted in substantially their present positions since the beginning of their existence, though their areas above sea-level had undergone considerable changes from time to time owing to variations in the relative level of land and sea. Many remarkable facts presenting very considerable difficulties in the distribution of animals and plants in the present and in the past were got over by the assumption of the appearance and disappearance of 'land bridges,' often supposedly thousands of miles long, across the existing oceans. When these assumptions came to be studied in the light of the doctrine of isostasy it was seen that the emergence, and perhaps even more the submergence to oceanic depths of such land masses was hard to explain, and was in any case in flat contradiction of the long-cherished doctrine of the permanence of ocean basins. As the knowledge of the general geology of the world increased other remarkable phenomena also came up for consideration, such as the occurrence in Arctic regions of tropical or semi-tropical plant-remains in Mesozoic and Tertiary strata, and indisputable evidence of wide-spread glaciations in low latitudes and in widely scattered localities (South Africa, India, Australia, South America). All these facts were very difficult to reconcile with the existing distribution of the continents in relation to each other and to the present position of the equator and poles. The first suggestion of a possible drift of the continents came from an American, F. B. Taylor, in 1910, but the idea is more widely associated with the name of Alfred Wegener, a German geographer who lost his life in the Greenland exploration of 1930. Among many other lines of evidence Wegener laid stress on several instances of a remarkable correspondence in the forms of continents when brought in contact on a map, or better still on a globe, the most remarkable being the case of South Africa and

South America, where the N.E. corner of Brazil fits very well into the Gulf of Guinea.

It is impossible to give here even a summary of the arguments for and against the theory. It must suffice to say that it has received support from a considerable number of geologists of wide experience, while it has for the most part been strongly opposed by mathematicians and geophysicists, who are unable to find any mechanical cause for the extensive movements postulated. The whole state of the controversy up to 1937 has been admirably summed up by Dr. A. L. du Toit, who from his wide knowledge of the geology of the southern hemisphere is a strong supporter of the drift theory. Perhaps the fairest thing to say now is that at any rate the theory of continental drift can no longer be dismissed as the fantastic speculation of a few cranks: it has to be regarded as a serious contribution to the study of many problems hitherto unsolved. There are several cases in geology of phenomena of first-class importance, admitted by every one to have occurred, which have as yet received no theoretical explanation of general acceptance; as, for instance, mountain-building and ice ages.[1]

Structural Elements of the Earth.—The most obvious division of the surface of the earth is into continents and oceans, but this is an over-simplication: there are, in fact, intermediate forms that have to be taken into account. Both lands and seas differ a good deal in their nature. In the lands there is a strong contrast between great areas of flat-lying strata like most of European Russia, and mountain chains of Alpine type where stratified rocks are twisted up into the most extraordinary convolutions. Again there is a difference between the abyssal depths of the oceans, and the shallow seas studded with peninsulas and islands, which may have again and again been uplifted to form land. In the same way there are great areas of land which in past times have again and again been submerged, as shown by vast accumulations of strata with marine fossils. Obviously there is a close analogy between the last two categories, while there is a fundamental difference between such a block as Africa south of the equator, which has probably never been submerged as a whole, and the deeper parts of the oceans. True continental blocks and oceanic depths are not interchangeable, whereas the shallow seas and the lands consisting of marine strata evidently are so. Since many or most of the strata composing such lands have been laid down in comparatively shallow water, either on the continental shelf or near its borders, these lands and the shallow seas now existing may be conveniently classed together as the *shelf-areas*.

[1] Wegener, *Die Entstehung der Kontinente und Ozeane*, Brunswick, 1st edition 1915, 3rd edition 1922 (translated into English by J. G. A. Skerl as *The Origin of Continents and Oceans*, London, 1924). The 4th German edition, 1929, contains much important new matter not included in the English translation. du Toit, *Our Wandering Continents*, Edinburgh, 1937, with a very complete bibliography.

It so happened that modern geology began in England, France, Germany and eastern North America, which are typical shelf-lands, and therefore there was a tendency to assume that the rest of the world was similar and that there had been everywhere a constant interchange of land and sea. But when the enormous depth of the greater part of the oceans was ascertained, and later the general absence of marine strata in great areas in the middles of the continents, there arose a doctrine of the permanence of ocean basins, which of course implied also a permanence of continental blocks. This was probably carried too far and may have to be modified considerably in the light of the theory of continental drift, if this is established. But even if a block has moved up and down isostatically, or laterally under the influence of unknown forces, it may still remain an entity.

Leaving the deep ocean basins aside for the present we may now proceed to consider the structure of the continents and the shelf-areas in a little more detail. As before stated research has now shown that in the interiors of the continents there exist immense areas of very ancient rocks, which in the earlier stages of earth-history have been compacted into solid masses that apparently reacted as units towards later crust disturbances, whatever may have been the cause of these. Such resistant blocks are now usually called *shields*. As examples we may mention the Canadian shield, the great area of Precambrian rocks around Hudson's Bay; and the Baltic shield, including Scandinavia and Finland. Peninsular India is another example, and so in the southern hemisphere are the southern half of Africa, Brazil, and probably the western half of Australia. The Antarctic continent may be another.

The question of the shelf-areas is a little more difficult to explain. As before stated Western Europe, usually regarded as a geological type area, belongs to this category. In point of fact Western Europe is only a fringe to the continent of Asia, to which Russia belongs geologically. This is easily seen on a globe, though hardly so apparent in ordinary maps, owing to the use of many scales in an atlas.[1] Europe is not a continent at all. The North Sea, the Baltic and the Irish Sea and English Channel are typical shelf-seas, only exceeding 100 fathoms in a narrow channel off the coast of Norway. On the other hand, the Mediterranean is fairly deep, owing to special causes. The land of Western Europe is mainly covered by shallow-water marine sediments and the whole constitutes a shelf-area, which at present is more land than sea. For the opposite case, where the shelf is more sea than land, the best example is the western half of the Malay Archipelago,

[1] Much loose thinking has been introduced into geology by the careless use of maps on different projections and with different scales. Worst of all are maps of the world on Mercator's projection which, for example, magnify Greenland about twenty times. The only safe medium for geological theorising is a globe.

where the sea between Singapore and Borneo though very wide is extremely shallow. The eastern half, though deeper, is studded with innumerable islands.

Without entering into a mass of detail it may be said that any region of the world where most of the geological systems are present and represented by marine strata of not excessive thickness is to be regarded as a shelf-area.

On the other hand, it has been found that the great mountain chains of the world are largely composed of marine strata of enormous thickness and of obviously shallow-water character. Now it is self-evident that shallow-water sedimentation can only be maintained for scores of thousands of feet if the floor of the sea sinks at the same rate as the sediment is deposited. Therefore it is concluded that the sites of future mountain chains must have been weak zones of the earth's crust where the floor was depressed concurrently with the deposition of the sediment: again, consistently with the doctrine of isostasy, the floor of the sea was depressed by the weight of the sediment piled on it. Why

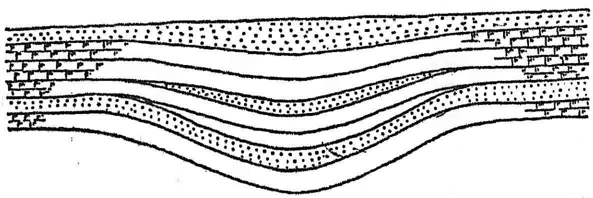


FIG. 68.—DIAGRAMMATIC SECTION OF A GEOSYNCLINAL. (After Haug.)

these weak zones in the crust should have existed we do not know, but undoubtedly they did exist. The typical example is the Mediterranean region which was afterwards crumpled up to form the Alpine chains. These weak zones are called geosynclinals (Fig. 68), since the arrangement of the sediments in them must be that of a syncline.

Therefore we see that the elements composing the earth's crust are the ocean basins, the continental blocks, the shelf-areas and the geosynclines. As we have just seen, geosynclinals are not permanent features, but can be converted by pressure into folded mountain chains: in the same way it seems possible that a shelf-area might be compressed and added on to a continental block, as mountain chains clearly have been, but in neither case is the reverse process possible. Hence it appears that there is a tendency for the continental blocks to grow at the expense of the weaker elements. It is a fact that in several instances the border of a continental block is formed by a fold-chain: e.g. the whole west side of both the Americas and the east side of Australia: the Pacific fold-belt of Western America is mainly of late geological date.

Plateau-building Movements.—This name is applied to those vertical uplifts and subsidences on a smaller scale which diversify the surface

of the continents; they may be described as producing minor platforms on the general surface of the continental masses, and are therefore to be regarded as a sub-class of epeirogenic movements. Structures of this kind are not largely developed in Britain, or, indeed, in Europe; to study them satisfactorily we must turn to Western America, where they have been worked out in great detail by the members of the United States Geological Survey. In the great plateau region of Colorado and Utah the following types of structure have been recognised:—

(1) *Uinta Structure.*—This is well seen in the Uinta Mountains. It consists of two large monoclinal flexures, in opposite directions, each with the downthrow on the external side, leaving a broad elevated

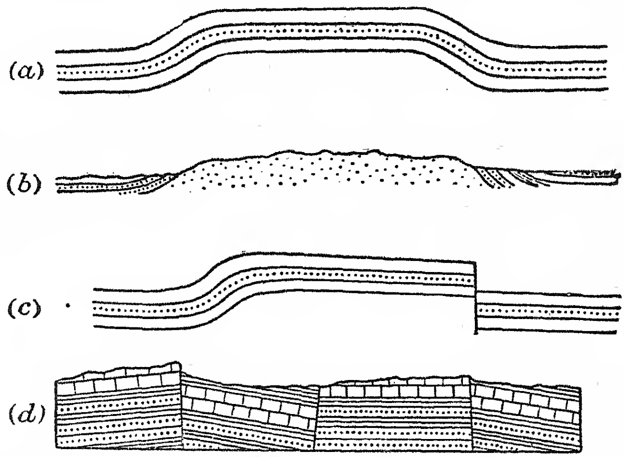


FIG. 69.—TYPES OF STRUCTURES PRODUCED BY PLATEAU-BUILDING MOVEMENTS. (After Powell, with slight modifications.)
a, Uinta structure; *b*, Park Plateau type; *c*, Kaibab structure; *d*, Basin-range structure.

tableland between them (Fig. 69 *a*). In the particular case referred to the flexure on one side passes over into a fault, with a throw of some thousands of feet.

(2) A special modification of this type is afforded by the *Park Plateau,* which constitutes the Yellowstone Park region, and appears to be connected with the intrusion of a mass of igneous rock below the uplifted portion. In the present state of our knowledge it is impossible to say whether the intrusion is the cause or the effect of the uplift, but at any rate it is clear that the two phenomena are intimately connected (Fig. 69 *b*).

(3) *Kaibab Structure.*—This name is applied when the discontinuity of the strata is more marked: here there is on one side a fault of very

large throw, without flexuring. The difference between this and the Uinta structure is only one of degree (Fig. 69 *c*).

(4) *Basin-range Structure.*—Here flexuring is still less conspicuous, and the whole area is broken up by faults into blocks of varying shape and size, tilted at various angles. The general result of the action of denudation on a region of this kind is the production of a number of hill-ranges composed of a clearly marked escarpment and dip-slope, the crest of the escarpment running closely parallel to the bounding fault on the upthrow side. This type is often spoken of as *block-structure* (Fig. 69 *d*).

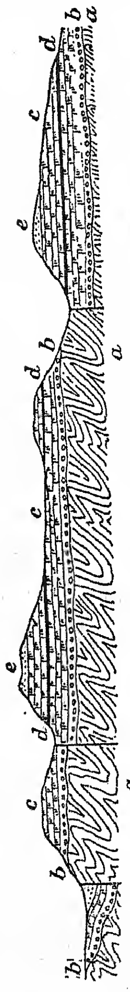


FIG. 70.—DIAGRAMMATIC SECTION ACROSS THE PENNINE CHAIN, FROM THE EDEN VALLEY TO THE RIVER TEES. Showing *block-structure*.
a, Pre-Carboniferous rocks; *b*, Basement Conglomerate of the Carboniferous; *c*, Lower Carboniferous; *d*, Whin Sill; *e*, Millstone Grit; *f*, Permian and Trias.

Block-structure in Britain.—As before stated, structures of such simplicity are rare in Britain, owing to the extensive prevalence in this country of mountain-building movements and their attendant folding and faulting of the strata. A good example is afforded by the fractures affecting the Carboniferous and older rocks of the Pennine chain in West Yorkshire, Durham, Westmorland and the east of Cumberland. The most important of these fractures are the Craven, Dent, Pennine and Tynedale faults, and these, with others of less importance, divide the country into a series of blocks at different levels. Conspicuous examples of fault-scarps are seen in the great scars near Settle, and in the Cross Fell range, which bounds the Eden valley on the east (see Fig. 70).

Horsts.—A study of differential movements has shown that certain well-defined blocks tend to stand up as hard and immovable masses, while the areas around them sink: these fixed masses are now generally designated by the German term *Horst*, for which there is no satisfactory equivalent in English (Fig. 71).[1] The Highlands of Scotland, north of the Grampian fault, and the Southern Uplands are good examples of horsts, while between them occurs the depressed area of the Central Valley. The Black Forest and Vosges blocks on either side of the Rhine valley may also be mentioned (Figs. 72 and 73). On a much

[1] The literal meaning of the word is eagle's nest or eyrie.

larger scale the African continent appears to be one of the most stable segments of the earth's crust, since it has apparently never been submerged since very early geological times. Horsts play a very important part in the economy of mountain-building movements, since they form

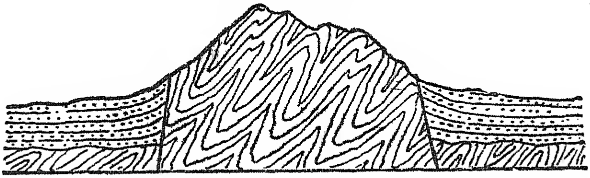


FIG. 71.—HORST MOUNTAIN.
This is the reverse of a rift-valley.

fixed masses which largely control the direction and results of lateral thrusts, when these occur in the same area. This will be clearly seen in a later section, when the trend-lines of the Alpine and other mountain-chains are considered. The ultimate reason why some parts of the crust are more stable than others is not known, but it is probably connected with the development of dominant structure-lines at a very early period of the earth's history.

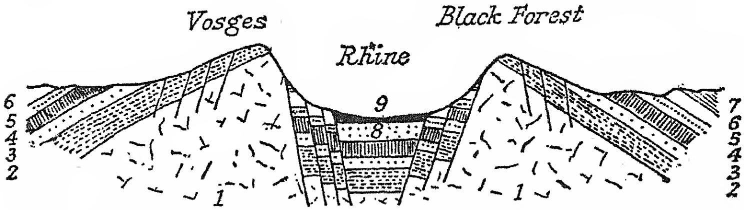


FIG. 72.—THE RHINE FLOWING IN A RIFT-VALLEY.
1, Granite; 2–7, Mesozoic rocks; 8, 9, Tertiary and Recent.

Rift-valleys.—Closely connected with block-structure and horsts are the remarkable long narrow sunken areas known as Rift-valleys or Graben. In these a strip of country has been let down between parallel faults to form a depression, and in one case at least part of the floor of such a depression is far below sea-level. This is the great Rift-valley of Syria and Eastern Africa, one of the most remarkable physiographical features on the face of the globe. This depression begins in Northern Palestine; it forms the valley of the Jordan and the Dead Sea: the surface of the latter is nearly 1,300 feet below that of the Mediterranean. From hence it is continued down the Gulf of Akaba and the Red Sea. Nearly opposite Aden it turns to the south-west, and soon splits into two branches. The eastern branch runs nearly due south, and contains Lakes Rudolf and Stephanie: it appears to die out in the neighbourhood

of Kilimanjaro. The western branch has a curved form, and gives rise to the great valley in which lie the Albert and Albert Edward Nyanzas, Tanganyika and Nyassa. All these lakes are long, narrow and deep, indicating depressions in the floor of the valley, which appears to be undulating. The Victoria Nyanza, on the other hand, is wide and shallow, and lies on the plateau between the two branches of the rift-valley. The valley appears to be everywhere bounded by faults, which are usually complex, in the form of step-faults, and the dip of the strata forming the bounding blocks appears to be generally away from the rift, as if the latter had been formed by the collapse of

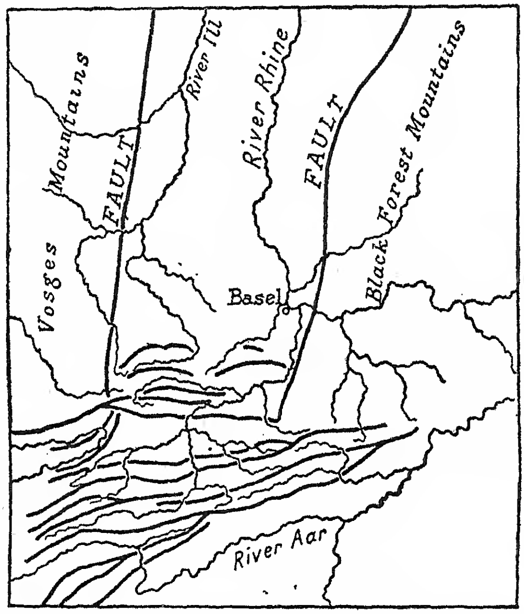


Fig. 73.—Map of Rift-valley of the Rhine.
The encroaching folds are seen to extend further down the valley, being retarded against the horsts of the Vosges and Black Forest Mountains.

the crown of an anticlinal arch. The foregoing is the interpretation usually accepted of this remarkable structural feature. But some geologists well acquainted with the country, or parts of it, have put forward a totally different explanation, namely, that the rift system is due to compression. According to this view the floor of the rift has been forced down by over-thrusting of the blocks on either side. The question can only be decided by further detailed work in all parts of this great stretch of country, some 5,000 miles long, and must therefore be left open. Possibly different explanations may be found to fit different parts.[1]

[1] Gregory, *The Rift Valleys and Geology of East Africa*. London, 1921.

The structure of the valley of the Rhine between the horsts of the Black Forest and the Vosges is very similar to this (Fig. 73), and the Central Valley of Scotland between the Highlands and the Southern Uplands is essentially a rift-valley. It is separated from the ancient gneisses and schists of the Highlands by the great Grampian fault, which has a maximum throw of some 14,000 feet. The Palaeozoic rocks of the Southern Uplands are bounded on the north by another fault nearly parallel to the Grampian fault, while the floor of the valley between the faults is occupied by comparatively undisturbed Old Red Sandstone and Carboniferous rocks, many of which are volcanic. It may be mentioned in passing that igneous rocks and volcanoes, both recent and extinct, are abundant in the African rift-valley, and indeed it seems that the formation of rift-valleys is usually accompanied by volcanic action.

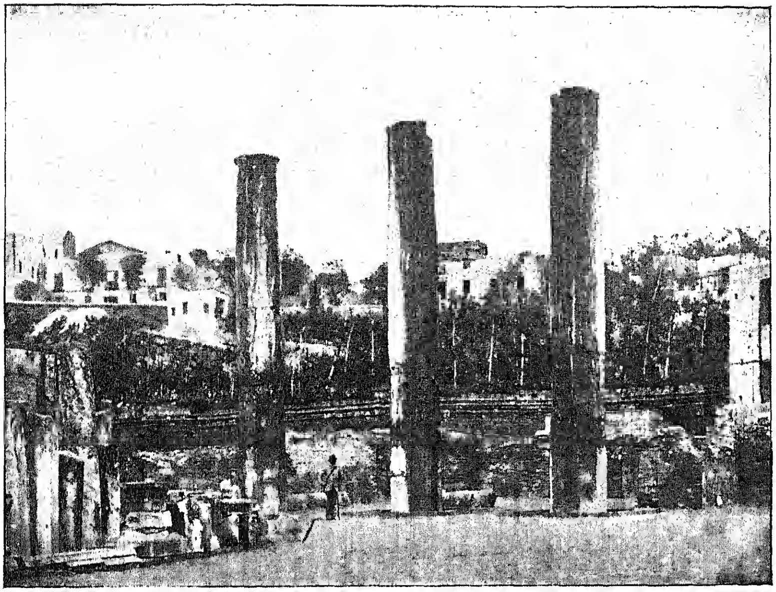
Submergence and Emergence of Land.—A detailed study of the lithological character and included organisms of the stratified rocks affords abundant evidence of the occurrence in past times of varying physical conditions, by which a large part of the earth's surface in the shelf-areas has been alternately raised into land and depressed below sea-level. Even at the present day there are to be seen along our coast-line clear indications of changes in the relative levels of land and sea occurring within recent times, and even now in progress. The most important physical features of recent date bearing on this point are the raised beaches and lines of cliffs whose base is now above high-water mark: these indicate emergence, while submerged forests and drowned valleys show a movement in the opposite direction. In the case of submergence the evidence is naturally more difficult to trace clearly, since the rise of the water-level conceals the handiwork of the sea at lower levels. When a beach or shore-line sinks beneath the waves its characteristic features are hidden from our sight and soon destroyed by marine erosion, or covered up by deposition of sediment. In many cases, however, submerged terrestrial accumulations, and even the handiwork of man, can be clearly seen, as for example in excavations for docks. In some districts the submarine topography, as revealed by soundings, gives unmistakable evidence of submergence or *drowning* of land.

Changes of Level in the Baltic.—One of the most satisfactory cases of change of level occurs in the southern part of Sweden on the shores of the Gulf of Bothnia, and this is of classic interest, since it was investigated by Celsius and by Linnaeus. The whole case is admirably summarised by Lyell in his *Principles*. Early in the eighteenth century the apparent fall of the sea in southern Sweden attracted the attention of Celsius, who estimated its rate to be about forty inches per century. He attributed the phenomenon to a general fall of sea-level all over the world, but it was soon pointed out that in other districts there was no evidence of such a general fall, but indications of a movement in the

opposite direction. In 1749 Linnaeus measured the distance between a large stone and the sea at Trelleborg, in the extreme south of Sweden, and in 1836 this distance was found to have decreased by 100 feet. Again, at Malmö, a few miles farther north, an ancient street pavement was found 8 feet below sea-level. It was evident on further investigation that the movement was not a simple vertical uplift or subsidence of the country as a whole, but varied in amount and in direction in different places. According to Lyell's summing up, Scania is sinking, whereas at Stockholm the land is rising 6 inches per century, and at Gefle, still farther north, 2 or 3 feet per century. As will be seen in the next section, in the north of Norway there is abundant evidence of recent elevation: hence it appears that the Scandinavian peninsula is being tilted round an axis a little south of Stockholm. The shores of the Baltic are, of course, specially suitable for this kind of investigation, as there are practically no tides to complicate matters.

Raised Beaches.—Where land has undergone emergence from whatever cause in recent times, old shore-lines are found above high water mark. These may be of two kinds: on the one hand there are terraces of shingle and ordinary beach material, often with shells, and, on the other hand, wave-cut platforms or terraces in rock or boulder-clay, with little or no loose material. Raised beaches or strand lines are specially characteristic of high northern and southern latitudes and are specially well developed in Norway, where they are found up to 600 feet or more. Moreover, it is found that when traced along a fjord towards its head they often rise in level, indicating that the middle of the country has been elevated more than the coast. This is thought to be due to a general isostatic recovery from the depression due to the weight of the ice-cap during the Glacial period, which would necessarily be thicker and heavier in the interior than along the coast.

Round the Scottish coast there is a series of raised beaches at various levels up to 100 feet above present high water mark. Of these, the most conspicuous occur at 100 feet, 50 feet and 25 feet respectively. The two higher ones date back to the Glacial period, as is shown by their fossils and their relations to the boulder-clays and other drift deposits. The lowest beach contains a fauna like that of the present seas. The raised beaches are traceable more or less continuously all round Scotland except in the extreme north, but the upper one, or hundred-foot beach, is only found in scattered places. The middle and lower beaches are very conspicuous features of the west coast, especially on the shores of Loch Linnhe and many of the sea-lochs opening into it, and also in the Isle of Skye. Raised beaches have also been detected on the shores of Morecambe Bay, near Pentreath in Anglesey, and in South Wales, Devonshire, Cornwall and the south of Ireland. One of these, in the neighbourhood of Cork, is clearly anterior to the oldest of the Irish boulder-clays.

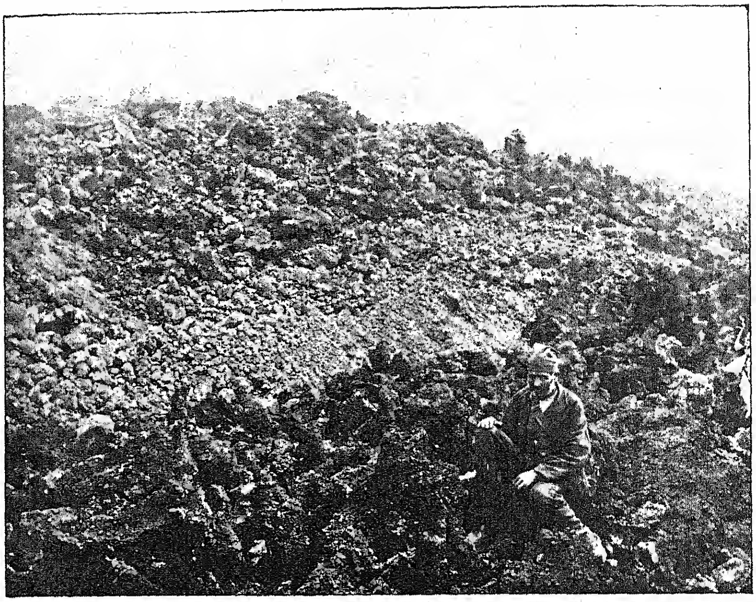


Tempest Anderson, photo.

(I) TEMPLE OF SERAPIS, POZZUOLI.

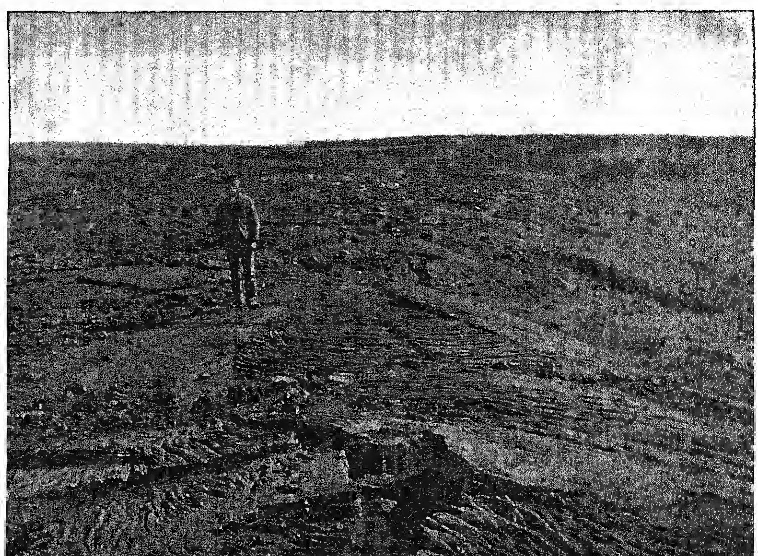
(II) MISTI, NEAR AREQUIPA, PERU. A CONE COMPOSED OF ASH, SHOWING THE CHARACTERISTIC CONCAVE CURVE.

PLATE XXIV



Tempest Anderson, photo.

(I) ETNA, LAVA OF 1886.



Tempest Anderson, photo.

(II) CORDED LAVA. MYVATN DISTRICT, ICELAND.

Submergence of Land.—On the other hand there is to be seen on many coasts conclusive proof that the sea now stands higher relatively to the land than it once did. It is hardly necessary to enter into detail as to the nature of the evidence brought forward to prove this point. In some cases the lower streets of ancient towns are now at or near sea-level, or have been swept away altogether. On the west coast of Greenland Eskimo huts may now be seen standing in the sea, and so on. In many lands there exist traditions of former cities now below sea-level, and even legends of lost continents, such as Atlantis and the Land of Lyonesse. In some cases there appears to be some foundation for these stories, and the existence of the drowned city of Ys, in the Bay of Douarnenez in Brittany, seems to be well established. There is no doubt, however, that in some places the effects of coast erosion have been mistakenly put forward as proofs of submergence; and in other instances the evidence is capable of more than one interpretation. The loss of great tracts of land and thriving seaports in eastern England seems to be entirely due to coast erosion.[1]

Changes of Level in the Bay of Naples.—An interesting case of oscillation of levels, which has given rise to much discussion, is that of the so-called Temple of Serapis at Pozzuoli, near Naples (Plate XXIII (i)). The chief remains of this building, which was probably a market rather than a temple, consist of three marble pillars about 40 feet high. Their surface is smooth up to 12 feet above the base; the next 9 feet are plentifully pierced by borings of *Lithodomus*; the remaining part of the pillars is untouched by boring animals. The pavement of the building is at the present time slightly below mean sea-level. Below this present pavement excavations in 1828 showed the presence of another at a depth of 5 feet. According to Lyell, the deposits which filled up the lower part of the building were composed of an alternation of calcareous sinter and volcanic ashes. The sequence of events here indicated is rather complex, but may be summarised briefly as follows. After the construction of the earlier pavement depression occurred, so that the building was reconstructed at a higher level, and the great pillars were then set up. Deposits of sinter and ash were formed inside this building to a height of 12 feet, and at a still later period depression occurred to a depth of at least 20 feet. The lower portions of the pillars were protected by the sinter and ash, but a zone about 9 feet high was exposed to the action of marine boring organisms, while the rest of the pillars was above sea-level. The most recent movement has been elevation, bringing the ground to its present level.[2]

By some writers all this has been attributed to variations of sea-level, but on other parts of the neighbouring coast-line there is evidence of both submergence and emergence of varying amounts in different places,

[1] See reference in footnote on p. 144.
[2] Lyell, *Principles of Geology*, 10th edition, 1872, vol. ii, p. 164.

quite inconsistent with general changes of sea-level, and it is clear that it was the land that moved. Pozzuoli is in a volcanic district, quite close to Monte Nuovo, which was active in the sixteenth century, and there is no doubt that the effects there seen are the result of real differential movements and disturbances of the earth's crust, acting in different directions at different times.

However, from what has been said above with reference to special cases, it must not be assumed that the level of the sea has never varied. A large depression of the sea-floor anywhere would necessarily lower the sea-level all over the world, unless, as seems probable, such a depression has to be compensated by uplift somewhere else. There is evidence that during the Pleistocene ice ages the general level of the oceans throughout the world was actually lowered considerably by the transfer of a large volume of water to the land in the form of ice. According to Professor R. A. Daly this lowering was as much as 200 or even 300 feet: it seems probable, however, that this estimate is exaggerated.

Submerged Forests.—Around the shores of the British Isles and elsewhere there are often to be seen beds of peat and vegetable soils containing stumps of trees in the position of growth, either between tide-marks or below the level of the lowest tides. In most cases these undoubtedly show submergence. It appears, however, that swamps may form behind shingle bars, at a level below that of the sea outside; if the shingle barrier is washed away and the swamp overflowed by the sea, a false appearance of submergence might be produced, so that the evidence from apparently submerged forests and peat-bogs must be received with some caution. Submerged forests have been observed at many points around the British coasts, and especially in Cheshire and Lancashire, on the shores of the Bristol Channel, along the English Channel, and near the mouth of the Tees. They are less common in Scotland but have been observed on the coast of Fife and elsewhere. Some of the best examples have been discovered during excavations for docks and harbour works. The close association of submerged forests and raised beaches in various places, especially in south-west England, has revealed a complicated history of alternate submergence and emergence in that region.

Mountain Building.—The origin of mountain chains is one of the most difficult problems of geology. There is no question that mountains exist and that they show an extraordinary complexity of structure, but up to now no really satisfactory explanation of these facts is forthcoming. However, an exception must be made in the case of a number of high isolated mountain peaks which are simply giant volcanoes: their origin is obvious and is discussed in the next chapter. The reference is to the much more important case where long ranges of high mountains are built up of sedimentary rocks formed in the sea, some

of quite recent geological date, as for example the Eocene marine limestones found up to 16,000 feet or more in the Himalayas. The first point to be noticed is that such mountains always do form long and comparatively narrow chains: they never occur for example in square or circular blocks. This must have a meaning. The next point is that the rocks composing such chains often include great thicknesses of strata of shallow-water origin, whereas the rocks of the same age in adjoining areas outside the chain are generally thin and of quite different lithological character. All these facts taken together have led to the conclusion that mountain chains originate in long narrow unstable areas undergoing depression and infilling by sediment—in short, geosynclinals.

The inference from all this is plain: that the geosynclinals have somehow been squeezed between approaching strong blocks of the crust and made to bulge up, with tremendous crumpling and compression. The difficulty is the theoretical explanation. Since opinions differ so much the subject will not be dealt with here. The object of this book is description of facts, not discussion of theories, many of which in this case are founded on unproved assumptions, while none have a secure basis of fact.[1]

Types of Folding.—The Jura mountains afford one of the best known examples of folding of moderate degree and simple type. This region has been studied with special care by many Swiss and French geologists and the results attained are more than usually reliable owing to the construction of many long railway tunnels, up to 5 miles or more in length. The strata include Permian, Mesozoic and Tertiary resting on a crystalline basement and one of the most notable features is that the later rocks, about 3,000 feet thick, have come unstuck from the crystalline basement, Permian and lower Trias, and slid towards the north, the salt and anhydrite beds of the Middle Trias acting as a lubricant (*décollement* of the French geologists). This shows that folding of this kind in a narrow zone, here about 30 miles wide, is a superficial phenomenon. In this instance the folding is more or less symmetrical with only an occasional overfold or overthrust to the north, as in the Grenchenberg and Hauenstein tunnels.[2] Evidently the pressure from the south was somewhat the more powerful. As is usual in this kind of folding each individual anticline does not extend very far along the strike but tends to die out and to be replaced by others having a parallel direction, but a little distance to the north or south, so that in plan the anticlines form a series of long, narrow, overlapping lenticles. Fig. 73 shows how the folds have encroached on the sunken rift-valley of the Rhine, whereas they are stopped by the horsts of the Vosges and

[1] The literature of the subject is enormous, much of the most important being in French and German. Advanced students will find very complete references in Bucher, *The Deformation of the Earth's Crust.* Princeton, 1933.

[2] See. Fig. 40 in Collet, *The Structure of the Alps.* London, 1936. The account of the Jura in this book is particularly clear and instructive.

the Black Forest. As will appear later the Jura folding is connected with that of the Alps and really represents the dying away of the pressure on the northern side of the Alpine geosynclinal. The Mesozoic strata continue for a long distance to the north flat-lying and almost undisturbed.

The Appalachian fold-belt of the eastern United States is of the same type as the Jura on a larger scale. The folded area is nearly 1,000 miles long and has a maximum width of about 125 miles. The area consists of an enormous thickness of Palaeozoic marine sediments of geosynclinal type and on the east lies a block of ancient crystalline rocks. The major pressure came from this side, hence the folds in this region are somewhat overturned and there are a few thrust-planes: the middle part consists of more or less symmetrical anticlines and synclines and the disturbance dies out gradually to the west in the gentle rolls of the strata in the Pennsylvanian coal and oil field, where oil-bearing structures show dips as low as one or two degrees. It is not known whether there is a discontinuity at the base, as in the Jura, but it has been calculated that one should exist, at least in the eastern half, at a depth of ten miles.[1]

Both here and in the Jura the topography is closely related to the structure, longitudinal valleys and anticlinal hill-ranges being conspicuous. Here and there rivers cut across the ranges in transverse valleys, some of which, in the Jura at any rate, are tear-faults.

Some examples of simple folding in the British Isles will be given later.

Folding of the types so far described is brought about with little or no change in the character of the rocks concerned, and no mineralogical changes, such as take place in the higher grades. The necessary adjustments are made by very simple means, such as opening and closing of joints,[2] sliding along bedding planes, plastic deformation of clays, faulting and irregular fracturing and a certain amount of brecciation: relative movements of rock-masses are often shown by slickensiding. When soluble rocks, such as salt, gypsum and anhydrite are present, strange effects are sometimes produced, of which the basal sliding in the Jura, already mentioned, is a mild example. These effects will be dealt with in a later section. It is obvious that in all questions of final structure as a result of compression and folding, the relative hardness of the rock-masses concerned is a dominating factor.

The Alpine Mountain-chain.—Most mountain systems are much more complex than the Appalachians, and present a much greater variety of structure. No region of this kind has been studied so exhaustively as

[1] For a very complete discussion of the Appalachian folding, with experimental illustrations, see Bailey Willis, *13th Annual Report of the U.S. Geol. Survey*, 1891–2. This work is a classic in the theory of mountain-building.

[2] It is self-evident that vertical joints must be opened in anticlines, which are regions of tension, and closed in synclines, which are compressed.

the Alps, and the phenomena there displayed may be briefly described as a type. The origin of the Alpine chains is undoubtedly to be referred to great thrusting movements, acting on the whole from south to north, with some local deviations. These thrusting movements resulted in the production of numerous parallel folds, which generally assumed a curved form, owing to the existence of horsts. These horsts cause the folds to deviate from the general direction, which is at right angles to the pressure, and the arrangement of the Alpine folds is curved. It is to be noted that the term Alpine system is used by modern writers in a very extended sense, to include not only all the mountain-ranges running from the south-east of France through Switzerland and North Italy into the Tirol and Austria, but also the chains of the Carpathians and the mountains of Transylvania, the Balkans, the Dinaric Alps, Crete and Cyprus, the Apennines, and the Atlas Mountains of North Africa. This system in its present form is of Tertiary age, though clearly founded on the ruins of earlier chains.

The structure of the Alpine mountain system and the mutual relations of its various parts can perhaps be most clearly seen in Moravia and Silesia, where the arrangements are simpler than in Switzerland or France. According to Suess and other writers, the whole may here be divided into three parts, from north to south, as follows: (1) the Foreland, (2) the chain of the Carpathians, (3) the sunken area of Hungary.

The name *Foreland* is given to the region composed of masses of older rocks which limited the extent and to a certain degree controlled the form of the Alpine system towards the north. In the area under consideration the foreland consists of three parts: the Russian platform to the east, the Sudeten Mountains in the centre, and the Archaean massif of Bohemia farther west. The Russian platform is composed of generally horizontal strata, while the Sudeten are a folded mountain-chain of much older date. The folds of the Carpathians have encroached on these structures, so that the horizontal rocks of the Russian platform and the Silesian coal-field are known to be continued under the folded chains, which here strike east and west, and can be seen to override the older folds of the Sudeten, which have a N.W.–S.E. strike. Farther to the west similar relations hold (see Fig. 73, p. 202); and in Western Switzerland the structure is further complicated by the interposition of the Jura region, and a broad area of low relief, the plain of Central Switzerland, between the Alps proper and the foreland.

The Alps.—Under this general designation is included the great mass of mountains forming the south-east of France, the south and east of Switzerland, part of Northern Italy and the Tirol. The Carpathians possess the same general structure, and are, as before pointed out, the direct continuation of the main zone of folding towards the east. By most recent writers the Alps of Switzerland are divided into two parts: (1) the Pre-Alps, which extend from Dauphiné past the Lake of Geneva

towards the north-east, and consist of Secondary and Lower Tertiary rocks, very highly folded and much overthrust; (2) the High Alps, comprising the most elevated portions of the mountain region, such as the Mont Blanc massif, the Valais Alps, and the Bernese Oberland. Of late years there has been, and still is, much controversy as to the actual structure of these two regions; in many parts there is evidence of extraordinary complexity, and numerous interpretations have been put forward by Escher von der Linth, E. Suess, Heim, Rothpletz, Schardt, Bertrand, Lugeon, Argand, Staub, Kober, Ampferer, F. E. Suess, Heritsch, Collet and many others. The whole subject is highly controversial and there are important differences of interpretation between the Swiss and the Austrian schools of Alpine geology. The student should be warned that it is not necessary to accept unreservedly every passage in the literature, since some things which appear to be simple statements of fact are in reality nothing but interpretations of difficult and often conflicting evidence. The great majority of the books on Alpine geology have been definitely written in support of some particular theory. It is unfortunately true that all along the

FIG. 74.—MOUNTAIN RANGE CARVED FROM A FAN-STRUCTURE.

interpretations put forward have been getting more and more complicated, and there seems to be little hope of any simplification.

The earliest and simplest interpretation supposed that the main chains of the Alps possessed what is commonly called fan-structure: that is to say a series of great arches, each composed of a number of subsidiary folds with axes dipping towards a central line. The result of the denudation of such an anticlinorial fan is to expose the oldest rocks along the central parts of the chain, while the flanks show narrow synclinal bands of newer rocks wedged in among the older ones and dipping under them. However, it was soon found that this explanation as a whole was inadequate. The most important part is played by recumbent folds with nearly flat axial planes, and therefore inverted lower limbs. In some cases these flat folds, which are called *nappes* in French and *Decken* in German, have been torn away from their *roots* and carried for great distances over the rocks below. Naturally there are often thrust planes and other forms of discontinuity between individual nappes, and a marked feature nearly everywhere is plastic deformation or rock-flow. Since rocks of all ages up to Middle Tertiary at least are involved in these strange contortions, it is obvious that the folding and flow were brought about under little cover. The mechanics of the process still remain a mystery.

But even this is not the whole story. When the Alpine chain is traversed from west to east, from Dauphiné to the Danube, higher and higher nappes are successively encountered, although the height of the mountains is if anything less. This means that the whole structure *pitches* towards the east, like a pack of cards that has been pushed gently towards one side. In several places towards the east owing to transverse elevations (culminations) of the crystalline basement erosion has gone deep enough to show lower nappes at the bottom of holes, so to speak, entirely surrounded by higher nappes; such structures are called *windows*, though skylights would really afford a better analogy. The Lower Engadine is largely such a window. In a sense the inverse of a window is what is commonly called by the German name *Klippe*, which is the equivalent of crag. These Klippen are, in fact, portions of an upper nappe, left isolated by erosion on the top of a lower one, which may consist of much newer rocks. They often form quite spectacular peaks, a famous example being the Mythen, near Schwyz, which consist of Jurassic limestones,[1] resting on Tertiary rocks, the lower part of the Jurassic being itself inverted. In most instances the base of a klippe may be conveniently regarded as a thrust-plane, and indeed all boundaries between nappes are essentially thrusts.

Although there are differences of opinion in detail, there is no doubt that the northward pressure was greatly preponderant; towards the northern margin there are folds of smaller amplitude in which the rocks have moved little from their original position; these are called *autochthonous folds*: in places they have been buried deeply under the recumbent nappes. Along the northern front of the main chain, beginning near the Lake of Geneva and forming the northern side of the Bernese Oberland, are many high peaks largely composed of Jurassic limestones; these are called the Pre-Alps, and it is believed that the nappes composing them have actually passed over the main crystalline chains from the Mediterranean region. Collet goes so far as to call them parts of Africa left stranded on Europe.[2] The higher eastern nappes, the Austrides, are also supposed to have travelled a long way from the south.

The East Alpine school of geologists maintain that in the eastern Alps the movement was essentially from east to west, not south to north as in the nappe region farther to the west, the eastern Alps being partly thrust over the western. Towards the east also the structure is different, being largely flat-lying thrust-planes with imbricated structure: flat folds with inverted middle limbs are not found, and the whole shows a considerable resemblance to the structure of the North-western Highlands of Scotland, to be described later.[3] There is also

[1] Collet, *The Structure of the Alps.* London, 1936, Fig. 63, and Plate X.
[2] Collet, *ibid.*, p. 21.
[3] Heritsch, *The Nappe Theory in the Alps.* London, 1929.

still some difference of opinion as to the relations of some of the ranges on the southern side of the Alps, some authorities holding that they are thrust towards the south, thus making the whole system ultimately a fan, though a very unsymmetrical one.

The Plains of North Italy and Hungary.—These represent the region of subsidence which always occurs on the inner side of a folded chain. The rocks are in a state of tension, due to the forward movement of the folded part of the system, and they tend to settle down in blocks, bounded by faults, so that the structure approximates to that of a plateau. Lombardy and Hungary thus form land areas of low elevation and low relief. But in other cases the subsidence has been so great that large areas have sunk below sea-level: the Adriatic, Tyrrhenian and Aegean Seas are of this nature, and they are closely connected with the formation of the Alpine and allied chains in Tertiary times.

Systems of Folding.—Turning now to a consideration of more general cases, we find that according to the arrangements of the folds several distinct types of structure can be recognised. As before stated, a series of parallel anticlines and synclines which are symmetrical, or nearly so,

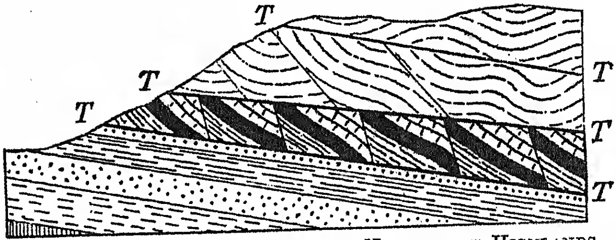


Fig. 75.—Imbricated Structure: North-west Highlands.
T, *T*, Thrust-planes.

is distinguished as the Jura or Appalachian type. When the thrust is more distinctly unilateral, so that overfolding to one side is pronounced, the structure is known as *isoclinal*. When the pressure has been intense the folds are often ruptured along their middle limbs, and the blocks thus separated are thrust over one another something like a pack of cards: this is known as *imbricated* structure (Fig. 75) and the divisional planes between the individual blocks are really of the nature of minor thrusts. These are very well developed in the North-western Highlands, where in many places the blocks between the major thrusts consist of many small 'scales' (*Schuppen*) formed in this way.

An assemblage of folds having the general disposition of an arch is called an *anticlinorium*; fan-structure is merely an exaggeration of this, where the squeezing has been so intense that the middle part of the folded zone has bulged out over the outer parts (see Fig. 74). In a similar way we may have a *synclinorium*, a series of folds which,

speaking generally, form a syncline (Fig. 76). The structure of North Wales, between the Menai Straits and Shropshire, belongs to this type.

Examples of Folding in the British Isles.—For the formation of a folded area of Jura or Appalachian type it is essential that the strata should be fairly uniform in character over a considerable area, and that the pressure should also act with a certain amount of uniformity. These conditions do not seem to have been attained anywhere in the British Isles, where the folded regions always show considerable complexity of structure, and there is generally much faulting and thrusting where the movements have been at all intense. The important disturbances which affected the strata of the south of England in Middle Tertiary times have given rise to structures of moderate simplicity, so far as concerns the Mesozoic and Lower Tertiary rocks. The south and south-east of England consists, broadly speaking, of two anticlines and two synclines with parallel axes. The synclines form the London Basin and the Hampshire Basin: these are separated by the broad arch of

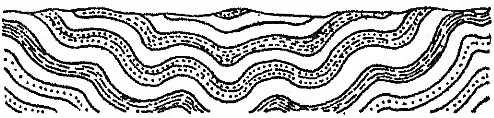


FIG. 76.—SYNCLINORIUM.

the Wealden uplift, which is itself probably an anticlinorium, and is continued westward through the Chalk Downs of Hampshire: the southern anticline of the Isle of Wight and the Isle of Purbeck has been in part dissected by the sea, but enough remains to show its original structure. This anticline is markedly asymmetric: in the Isle of Wight the northern limb is vertical, and in the Isle of Purbeck the beds are even inverted, the anticline passing over into a reverse fault or thrust-plane.

One of the most conspicuous anticlinal arches in the British Isles is that which forms the southern part of the Pennine chain in Derbyshire and the south of Lancashire and Yorkshire. The movement which gave rise to this uplift is of an age intermediate between the Carboniferous and the Permian, since the Carboniferous rocks are folded, while the Permian strata lie almost horizontally on their denuded edges. Of approximately the same age is the folding which has affected the Devonian and Carboniferous strata of Devonshire, and a good example of isoclinal folding is to be seen on a small scale in the cliffs and on the beach at and near Ilfracombe. Reference has already been made to the imbricated structure and thrust-planes of the North-west Highlands, and these will be described more fully in the stratigraphical section of this book. They are developed on a great scale, but some of the thrust-planes of the Alps and Scandinavia are of even greater

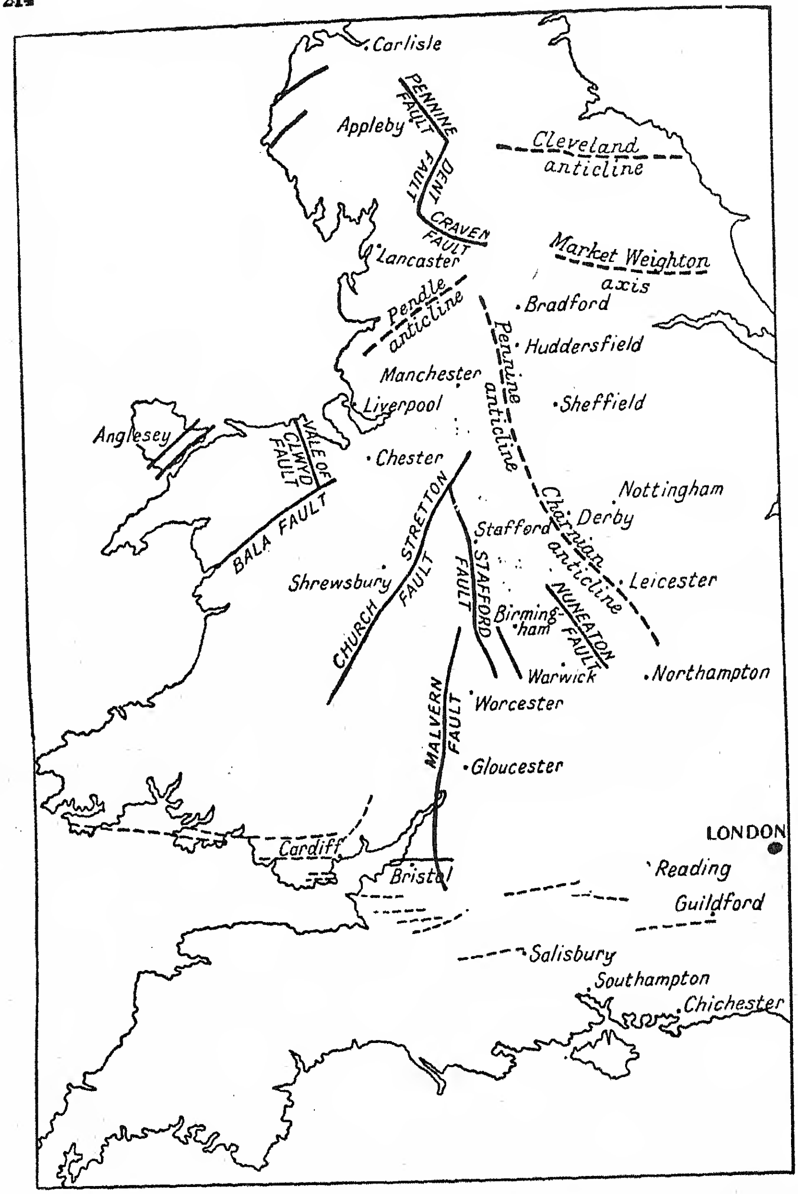


FIG. 77.—MAP OF THE PRINCIPAL FOLD-LINES AND FAULTS OF NORTHERN ENGLAND AND WALES.

After Sir A. Strahan, *Rep. Brit. Assoc.*, 1904, Plate viii (with slight alterations and additions). Continuous lines are faults, broken lines are anticlines.

magnitude. In most of the cases referred to, the upper blocks have moved forward farther than the lower, but in explanation of certain peculiarities of structure and outcrop observable in the English Lake District it has been suggested that the lower blocks have moved forward farther than the upper ones. This may also be expressed by saying that the upper blocks have lagged behind the lower (Fig. 78). The

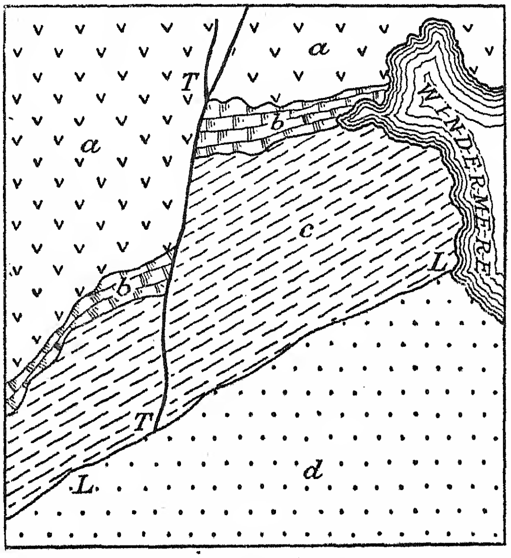


FIG. 78.—MAP SHOWING FAULTS TO THE WEST OF THE HEAD OF WINDERMERE (After Marr.)

a, Volcanic Rocks; *b*, Coniston Limestone; *c*, Coniston Flags; *d*, Coniston Grits; *L*, *L*, Lag Fault; *T T*, Tear Fault.

planes along which relative displacement has occurred are therefore called *lag-planes*. In this connexion it may be observed that the term *overthrust* is founded on an assumption that the upper blocks moved forward: this is not in all cases demonstrated, and a backward movement of the lower blocks, or *underthrust* in the opposite direction, would produce precisely the same effect, so far as the resulting geological structure is concerned. It is believed that this has often occurred.

Frame Folding.—In North Germany and Holland as well as in parts of western North America, a peculiar type of structure usually known as *frame folding* (*Rahmenfaltung*) is of considerable importance. It seems to come about when areas of more recent sedimentation have been subjected to pressure between fold-ridges of older date, which form the frame. The result is that the newer rocks with their older foundations are broken up into blocks that undergo differential movement, tilting and bending, and even slight overthrusting. On the other

hand some of the phenomena suggest occasional tension and settling, probably alternating with the compression. So far as the writer knows, no comprehensive account exists in English of this type of structure, which has been found to be of great significance in explorations for coal, salt or oil in North-western Germany and Holland.[1] It is possible that the region thus disturbed about Portlandian times extends under the east of England.[2] The general name employed in Germany for the disturbances of this epoch is the *Cimmerian fold system*, from the Crimea, where it began about the end of the Trias and travelled slowly north-westwards across Europe. This is one of the clearest cases we have of the progress of an earth-wave.

Superficial Effects of Earth-movements.—Geological processes are so slow in their action that it is usually impossible to observe them in progress. However, such movements are occasionally manifested by earthquakes and their accompaniments; rock-falls, landslips, faulting, elevation or depression of the land. Moreover, the mere existence of steep slopes, whether due to uplift or simply to denudation often occasions soil-creep or rock-creep, which of course are closely related to landslips.

Intensive exploration in the almost vegetation-less oil-bearing areas of Persia has revealed some remarkable structural features which can only be explained as being due to sliding, bending and folding of rocks now undergoing denudation, these effects being solely due to gravity at the surface, although their elevation into the present mountain ranges is of course due to folding of the ordinary orogenic type. It is common enough for masses of hard rock overlying softer ones to slide or fall down during denudation, but in this area large sheets of rock, measurable by miles, have not only slipped, but have actually undergone pronounced folding and even inversion. The rocks concerned are massive limestones, interstratified with marls, gypsum and other plastic types. Details cannot be given here: reference should be made to the literature, which is accessible in any geological library.[3]

Salt Plugs and Salt Domes.—A most remarkable subsidiary effect of folding is seen in several areas where the strata include important beds of rock-salt, gypsum and other soluble salts. Salt-domes are numerous in the frame-folded area of North-western Germany, where many are exploited and therefore their structure is well known in detail, and also in the oil-bearing Gulf Coast region of the United States. Some of the most remarkable occurrences are in South-western Persia (Laristan) where plugs of salt have broken through an enormous thickness,

[1] See Bucher, *The Deformation of the Earth's Crust*. Princeton, 1933, pp. 158 and 322, with references, especially to the writings of H. Stille. A short description will be found in Arkell, *The Jurassic System in Great Britain*. Oxford, 1933, p. 87.

[2] Rastall, *Geological Magazine*, lxiv, 1927, p. 10.

[3] Harrison and Falcon, *Geol. Mag.*, lxxi., 1934, p. 529, and *Quart. Jour. Geol. Soc.*, xcii, 1936, p. 91.

perhaps up to 20,000 feet, of folded strata and have reached the surface. At the outcrops the salt often flows and makes a very good imitation of a glacier. A strange feature here is that the salt has brought up with it masses of Cambrian and perhaps older strata not otherwise known in the region. The salt-plugs, some of which have an area of several square miles, and one of 40 square miles, have usually broken through an anticline or a dome, without much apparent relation to structure. It is not clear whether they have been forced up by the mere weight of the folded rocks, or whether tangential forces were still in operation at the time of their intrusion. In some cases at any rate the salt still appears to be in movement.[1]

At one time it was believed that soluble salts had been carried in solution into domes and other suitable structural features where pressure was relieved, but in the Persian instances this was certainly not the case, as solutions could not have carried up the Cambrian rocks: in many German salt-domes also the intense contortion seen in the salt-beds negatives this idea. The actual transport is now attributed to plastic flow and to a considerable extent it simulates the movement of glacier ice.

Compression in Folded Chains.—It is obvious that when a geosyncline, originally consisting of flat-lying or gently dipping marine strata, is crumpled up by tangential pressure into a fan, an anticlinorium or a mass of recumbent folds, there must be a very considerable shortening of the distance between the edges of the approaching blocks, the jaws of the vice. Many attempts have been made to estimate the amount of this shortening in different instances, but the figures given for the same system by different workers vary so enormously, often from tens to hundreds of miles, that it is quite useless to quote any actual examples: so much depends on the interpretation of the structures. It is easy to see that the nappe theory of the Alps involves much greater compression than a simple fan, and in the case of a structure of the North-western Highland type, consisting mainly of thrusting of blocks without folding, it is difficult to see how any figures of value could be arrived at. Here the rocks above the highest thrust, the Moines, are unlike any of those below: hence it is impossible to ascertain how far they may have travelled. It is not a question of unravelling a tangled skein, and measuring the wool, but of estimating how much differential movement has taken place between totally unrelated blocks. This consideration applies with equal force to the eastern Alps.

Orogenetic Zones.—It has already been explained that mountain chains arise on the site of long narrow previously depressed areas called geosynclinals. A notable feature in the distribution of such orogenetic zones is their tendency to occur at the margins of the great continental blocks. This is specially notable in the Pacific, which is very largely

[1] Harrison, *Quart. Jour. Geol. Soc.*, lxxxv, 1930, p. 463.

bounded by mountain chains of not very ancient date, mainly Tertiary: many of these are more or less curved and some take the form of festoons of islands; e.g. the Aleutians, the Kurile Islands and Japan. As already pointed out the Alpine geosynclinal in the broadest sense is regarded as having been squeezed between Africa and Europe, while in Asia the Himalayas are linked on to the European part of the Alpine system by the broad belt of mountain ranges of the Caucasus, Asia Minor, Iran, Afghanistan and so on. Earlier in geological history the whole of this enormous area was a great sea, now called Tethys, of which the Mediterranean is a shrunken remnant, its present diminished size being due to the closer approach of the northern and southern continents.

Some writers regard each chain in the Mediterranean region as arising from a separate geosynclinal, whereas others, especially Kober, consider that the whole region from the Jura to the Atlas mountains represents one large geosyncline, with fold-chains on its northern and southern margins, and an intermediate region now partly foundered, forming the Mediterranean, the Adriatic, the plains of Lombardy and Hungary, etc. Much difference of view has arisen as to the relations of the isolated chains of southern Europe: the Pyrenees and Sierra Nevada in Spain; the Balearic Isles; Corsica and Sardinia; and other land masses. On this theory also the position of the Dinaric Alps in the scheme, and the relations even of the Apennines to the Alps are by no means clear. Many attempts have been made to construct maps linking up all the chains into a connected system, but in the present state of our knowledge all this must be regarded as highly speculative.

Orogenetic Epochs.—A study of the stratigraphical succession in almost any part of the world shows that mountain building is localised in time as well as in space. In some regions it has rarely or never occurred, at any rate since the Precambrian, while in others it is definitely restricted to certain periods, with long intervals of quiescence between. So far as concerns the British Isles this is elaborated in the last two chapters of this book. However, although the British periods of disturbance can be matched in North-western Europe and to a considerable extent in North-eastern America, they are by no means world-wide. In fact it would probably be nearer to the truth to say that in the southern hemisphere the orogenetic epochs alternate rather than coincide with those of Europe, though this is perhaps an overstatement of the case.

It has often been pointed out that successive fold-belts have frequently arisen alongside of older ones: thus, for example, the structure of Europe has mainly been built up by addition of strongly folded belts, each to the southward of its predecessors. This is well illustrated by the geological history of the British Isles, which is to a large extent an epitome of that of Europe. There is probably no other region of the

world of equal size whose geological history is so complete, and this fact has had a far-reaching influence on the development of the science and on its nomenclature.

Another point of much importance, emphasised long ago by Bertrand, is the tendency for folding to recur at later dates along the same lines as in earlier systems. This may be illustrated by the analogy of crumpled paper or corrugated iron, where further pressure would mainly accentuate earlier effects. This principle of *posthumous folding* is very clearly shown in southern England, where the Tertiary folds described in a preceding section of this chapter follow almost exactly the trend-lines of the earlier Armorican or Permo-Carboniferous folds, while in the southern Midlands posthumous uplifts of ancient buried N.W.–S.E. (Charnoid) axes have had important effects on Jurassic and Cretaceous stratigraphy.

Mountain Building and Igneous Activity.—Although for the sake of simplicity little or nothing has been said about it in this chapter, nevertheless, igneous activity of various kinds is a very common accompaniment of earth movement. Often it is a direct result of the production of lines or areas of weakness in the crust, either by tension or by compression with fracture. Thus many mountain chains consist in part of volcanoes, although here the vulcanicity is properly to be regarded as a secondary effect only, and not the prime cause of the uplift. Some of the island festoons of Asia are very rich in volcanoes, e.g. the Aleutian islands, Japan, the Philippines, and above all Java and Sumatra. The Andes is another highly volcanic chain, and extinct or dormant volcanoes are found in the north-western part of the United States and in Alaska. The curved island arc of the Antilles also carries volcanoes and the volcanoes of the Mediterranean are no doubt secondary effects of the foundering of that area. Other volcanic regions of the world, especially Iceland and Central Africa, are probably subjected to tension.

Many of the points here touched upon are elaborated in the two following chapters.

Again earth-movements are often the direct cause of intrusions of molten igneous material, in some cases perhaps partly to fill up cavities due to uplift or up-bending of strata, although it is probable that the molten material follows the movement so closely that no actual empty space ever exists. Great masses of igneous rock are often found along the cores of anticlines, and it is in many cases a matter for discussion whether this is due to the actual intrusion of a liquid by flow, or whether the igneous rock really represents the fusion and recrystallization in place of the rocks originally occupying the space. In many parts of the world swarms of parallel dykes are almost positive proofs of a stretching of the crust.

The relation between earth-movements and igneous activity in the British Isles is discussed in Chapter XXVIII.

CHAPTER XI

VULCANICITY

Definition of Vulcanicity.—As stated in the concluding section of the last chapter, there is a very close connexion between earth-movements of all kinds and vulcanicity, this word being here used in the broadest sense, to include not only the phenomena shown by volcanoes in all their forms, but also the manifestations of igneous activity within the earth's crust: in other words, intrusive as well as extrusive action. The eruptions of volcanoes and the intrusions of igneous rocks are phases of the same form of activity under different conditions and cannot logically be separated. In the present chapter we shall deal mainly with the superficial or extrusive effects, leaving the nature and forms of the intrusive masses and the petrographical description of igneous rocks of both categories for the following one. It will also be convenient to postpone discussion of the causes of vulcanicity until the actual phenomena have been described.

Products of Volcanoes.—The products of vulcanicity may be emitted in the gaseous, liquid or solid forms. They vary much in character in different cases, and also during different phases of the activity of the same volcano. It would be easy to construct a very long catalogue of substances formed in connexion with volcanic eruptions, but many of these are of little or no importance, and may for our present purpose be disregarded. In the case of many of these rare substances it is also difficult to determine whether they are actual and original products of the volcano itself, or whether they have been formed by subsequent changes and the introduction of material from outside sources. It is only when any substance occurs repeatedly and in large amount that we can be quite sure that it is a true and characteristic product of the actual eruptive activity of the volcano.

It is most convenient to begin with the gaseous products of eruption, since they may be regarded as in some way partaking of the nature of cause as well as of effect. It is the evolution of gases on a large scale which, in the majority of cases, if not in all, is the actual dynamical agent by which the liquid and solid products are raised to the surface or ejected from the crater. The extreme importance of water in connexion with the phenomena in question will be considered in a subsequent section, when we come to deal with the causes of vulcanicity. Steam is emitted in vast clouds during nearly all eruptions, and it evidently forms the motive power of the explosive activity. In the later stages

of the life-history of many volcanoes, as will be seen in the sequel, steam and hot water are the sole products.

The presence of hydrogen has been noted during many eruptions, and in one or two cases oxygen has also been stated to occur: this has been supposed to indicate that the constituents of water may be dissociated in the magma: if so, their sudden recombination on a fall of temperature would also give rise to explosive energy. Hydrocarbons occasionally occur, especially marsh gas, and the combustion of these hydrocarbons and of hydrogen gives rise to the pale, lambent flames sometimes seen during an eruption. These flames are quite unimportant, and are the only instances of true combustion connected with vulcanicity.

Gaseous compounds of sulphur are very common, especially sulphur dioxide and sulphuretted hydrogen. These and other gases, by their mutual reactions, give rise to the deposits of sulphur so characteristic of volcanic districts. Some, however, of the so-called deposits of sulphur described by non-scientific travellers are found really to consist of ferric chloride, which is very similar in appearance. This is produced by reaction between the iron compounds of the lava and the hydrochloric acid which frequently occurs in volcanic vapours. Sublimations of crystalline ammonium chloride are often found in craters, due to deposition by vapours, and the occurrence of similar deposits of sodium chloride has been cited in support of the idea that eruptions are due to access of sea-water to heated material.

In a few instances boric acid is found as an important constituent of volcanic vapours. This, however, occurs only under special conditions. The only other gaseous product remaining to be mentioned is carbon dioxide: this is commonly given off in large quantities during the very latest phase of the activity of a volcanic district. In a later section examples will be cited of the occurrence of these various constituents, and it will be shown that each indicates more or less definitely a stage in the life-history of a volcano.

Turning now to the liquid products of eruption, we find that they are for all practical purposes only two in number, viz. water and lava.

During the eruptions of normal volcanoes the temperature is so high that all the water is given out in the form of steam, but so soon as this steam comes in contact with the colder layers of the atmosphere it is condensed and descends again in the form of rain. Torrential rains are a very common accompaniment of great eruptions, and they often do more damage than the showers of ash or streams of lava. Sometimes these heavy rains, falling on accumulations of fine ash and dust, produce gigantic flows of mud which nothing can withstand. It was in this way that Herculaneum was destroyed. An eruption may also produce destructive floods in another way; many of the greater volcanoes of the world rise above the snow-line, and are thus sometimes

capped by great quantities of snow and ice. If this is suddenly melted, great floods may be produced. In 1877 a stream of lava overflowed the crater of Cotopaxi, and melted some of the snow and glaciers near the summit. The result was a great flood, which travelled for an immense distance at the average rate of twenty miles an hour, and devastated much of the surrounding country. Since some heavy machinery from a cotton mill was carried nearly thirty miles, the geological effect of such a flood must be very great.

Water produced in this way cannot, however, be regarded as a true and direct product of volcanic action, though its ultimate geological effect is much the same as if it was actually poured out of the crater in streams. There are cases of true eruptions in which water in the liquid state is the most important, or the only, product. These include such phenomena as geysers, hot springs, mud-volcanoes and so forth. These, again, are manifestations of expiring activity, and will be described in due course.

The other liquid product, lava (Plate XXV), is of a much more complex character. It is of the greatest geological importance, since it is the raw material of all the igneous rocks, both extrusive and intrusive. The study of the nature and composition of these rocks forms an important part of the science of petrology, but as this requires separate treatment, it must suffice for the present to say that lava may be defined as molten rock-material. The degree of fluidity of a lava depends very largely on its composition. An acid lava, when raised above its melting-point, remains very viscous for a long range of temperature, while a basic lava under like conditions quickly becomes highly mobile. This has a very important bearing on the forms of mountains built up of lava-flows.

The majority of volcanoes eject more or less of their products in the solid form, and the nature of these varies to some degree (Fig. 79). It is obvious that at the first formation of a vent, the material most likely to be thrown out will consist of fragments of the rock through which the opening has been made. Some of the crater-lakes of the Eifel are surrounded by a low ring mainly composed of fragments of the country rock, a slate of Devonian age, and many other volcanoes occasionally throw up fragments which have been torn from the sides of the pipe. These fragments are often highly metamorphosed. A good example is afforded by the blocks of altered limestone which are found at Vesuvius, and often contain rare minerals.

By far the most important of the solid products consist of lava-material, which has either solidified before ejection from the crater or during the process. If liquid lava is carried up into the air in a finely divided state by explosive action, it will be cooled very rapidly and will reach the ground in a solid form. More important even than this is the material which solidifies within the crater and pipe of the volcano.

If a volcano has been quiescent for a time a thick crust will form over the lava-reservoir, and the first effect of renewed activity will be the breaking up and blowing out of this crust. It is usually ejected as angular fragments of varying size, and forms the material known as agglomerate or volcanic breccia, which is so characteristic of the explosive type of eruption.

Even when a volcano is in a more or less continuous state of activity, with molten lava in its crater freely exposed to the air, a solid crust is constantly being formed and broken up again by the circulation of

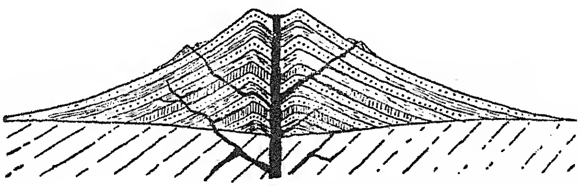


FIG. 79.—SECTION ACROSS AN IDEAL VOLCANO.

convection currents in the lava. This formation and breaking up of crusts has been observed again and again in the case of the great craters of Hawaii and many others. When the activity becomes rather greater than usual, that is, when an eruption occurs, some of this solid material is blown up into the air and falls beyond the limits of the lava-lake in the crater. In this way large cones may be built up (see Plate XXIII (ii)).

Special names are applied to this class of solid product according to its character: when it is very vesicular and, in fact, consists of the solidified froth and scum from the surface of the lava, it is called *pumice*, especially when of acid composition and so full of cavities as to float on water. Pumice really consists of glass of specific gravity about 2·5, and its apparent lightness is entirely caused by its spongy, cellular structure, due to the inclusion of a large amount of steam and gases in the lava from which it was formed. The term *scoria* is used for material of a rather more cindery nature and usually of more basic composition. It has essentially the same origin as pumice, and the slight differences are due to variations in the character of the lavas from which the two are derived. The name of *lapilli* is often applied to small stony masses varying from the size of a walnut to that of a pea or rather less. If the material is still more finely divided it is spoken of as volcanic sand or dust, and the latter is often in the very finest state of division, so that it is carried in the air for immense distances. Masses of volcanic dust, especially if partially or wholly solidified, are often designated *tuffs*. It is better to restrict this term to those accumulations which have subsequently become consolidated. Many

of the above described materials are frequently spoken of rather vaguely as volcanic *ashes*. The term has no very precise meaning, but usually seems to imply a moderately fine state of division. *Bombs* are masses of lava, usually of a somewhat rounded form and often of considerable size. They are generally ejected in a more or less viscous condition, and become rounded during their passage through the air.

Physical Characters of Lavas.—The chemical and mineralogical composition of lavas is described in the next chapter, but a few of their noteworthy physical characteristics may be briefly mentioned here. The influence of chemical composition on viscosity and therefore on the forms of flows has already been discussed. Besides the formation of pumice and scoria mentioned above, among other notable features serving to distinguish a flow from an intrusion is the so-called vesicular structure: that is, the presence of spherical or oval cavities due to steam. When these are filled with secondary minerals, often light coloured, they are called *amygdales*, from their resemblance to almonds in a cake. Sometimes when lava runs over damp ground the steam thus generated forms more or less vertical tubes at the base, sometimes several inches long (pipe amygdaloids). When lava is cooled quickly in contact with water it often assumes what is known as *pillow structure*; that is, it looks like a pile of sacks or pillows. This is commonly supposed to be characteristic of eruption in very deep water, but the late Dr. Tempest Anderson saw and photographed the formation of pillows in a lagoon in Samoa.[1]

Fissure Eruptions.—In the simplest and in some respects the grandest type of eruption there is no cone or crater in the ordinary sense, and very little explosive action. It is perhaps fortunate that eruptions of this kind are not now in progress in any part of the world, but they have played a great part in the past, giving rise to by far the largest known masses of igneous rock, which is always basalt. In the ideal case, the crust is in a state of tension and lava pours out through great parallel fissures, usually in successive flows extending through a long period of time. Each individual flow is not usually very thick, rarely exceeding 100 feet and averaging about 20 feet, but the total may amount to several thousands of feet. In many instances there must have been a considerable interval of time between successive flows, as the tops of each may be considerably weathered, while here and there old plant beds are preserved; from these the age of some eruptions has been determined. The fissures serving as feeders of the flow are of course left filled with basaltic material and constitute a system of dykes, usually, more or less parallel over a large area; their width is rarely more than 50 feet and usually a good deal less. It is doubtful, however, whether in any case the story is quite so simple as above outlined:

[1] Anderson, *Volcanic Studies*, 2nd Series. London 1917, p. 59, and Plates XLIX and L.

usually there are complications due to large intrusive masses or to occasional explosive activity.

This type of eruption was first clearly described and explained by von Richthofen in the case of the Snake River plains in the Great Basin region of North America. He called attention to the complete absence of cones and craters, and suggested the term 'Massive Eruptions.' They are now commonly spoken of as 'Fissure Eruptions,' and the resulting lava-flows are often called 'Plateau Basalts.'

The basalts of the Snake River plains cover an area of some 200,000 square miles, and their maximum thickness is about 5,000 feet. The Deccan plateau in Central India is larger still, and if certain outlying patches are taken to indicate former extension, it once covered 400,000 square miles of the Indian peninsula. But the lavas are thickest, nearly 10,000 feet, on the west coast in the neighbourhood of Bombay, and this suggests that they once extended to a much greater distance in this direction. The Stormberg lavas of South Africa are mainly due to fissure eruption.

For many years it was believed that the great masses of basalt lava covering over 2,000 square miles in North-east Ireland and in the Western Isles of Scotland belonged to this simple type, but it is now recognised that they form part of a much more complicated story, as will be set forth later.

The Icelandic Type.—Closely related to fissure-eruptions is the form of vulcanicity now seen in Iceland, and this presents several peculiar and interesting features. The volcanoes of this island have been carefully studied by Thoroddsen.[1] This author recognises three different kinds of eruptive vents, viz. (1) cones built up of both ash and lava; (2) cones built up of lava alone; (3) chains of craters. The first two correspond closely with the Vesuvian and Hawaiian types, presently to be described; but the third kind is by far the most common. In the south of Iceland all the volcanoes are arranged along fissures running south-west and north-east; in the north of the island the fissures run north and south. The chain-volcanoes consist essentially of a large fissure along which are numerous small ash cones, usually not exceeding 350 feet in height, and often very steep, with craters at the top. Sometimes the cones are separate and distinct, but commonly the point of eruption moves on, so that the craters intersect. Occasionally enormous floods of lava are given out from these crater-chains, as in the well-known case of Laki in 1783, when two separate streams of basalt flowed for 40 or 50 miles, with maximum widths of 15 and 7 miles respectively. Sometimes also flows of basalt issue from fissures without cones: these are generally small, but one such fissure is 20 miles long and has poured out sufficient lava to cover 270 square miles.

[1] *Geog. Journ.*, xiii., 1899, p. 500.

Another curious type characteristic of Iceland is that described by Reck as 'areal eruption.' In a small-scale example near Reykjavik about 100 small craters with diameters of less than 100 yards, usually much less, are scattered closely over an area of about 1 square kilometre. The same author describes larger-scale examples in East Africa and Syria. In these there is no linear arrangement, and the whole suggests a wide magma-basin at no great depth.

Volcanic Cones.—In most cases the centre of activity is still more localised, and may be regarded as concentrated at a point instead of being distributed along a line. When this occurs we get what is commonly known as a volcano, and these true volcanoes usually build up some kind of a cone or hill of accumulation round the orifice. The structure of this cone depends on the nature of the material ejected, and its size on the magnitude and duration of the eruptive activity.

Material may be ejected from volcanoes in the gaseous, liquid or solid form. The first of these can play no constructive part, but acts chiefly as a motive power; it is also at times destructive, as will be seen later; matter in the solid state, and certain of the liquid products when consolidated, are constructive, and build up the cone.

In a few cases the whole history of a volcano seems to be confined to a single explosion, which simply drills a more or less round hole through the crust without any further action. This leaves a hollow or crater surrounded by a low ring of fragments of the country rock. Such explosion-craters are often occupied by lakes, as in the Maare of the Eifel district in Germany. Usually, however, activity lasts longer than this. Sometimes a single phase of activity may give rise to a considerable cone, as in the case of Monte Nuovo, near Naples, which is 440 feet high, and was formed in two or three days, in the year 1538. Such youthful cones almost always consist entirely of fragmentary material, and the outpouring of lava belongs to a later stage in the history of the volcano. A very common result of the uprise of lava in an ash cone is the breaking down of one side of the crater, owing to the weight of the molten mass within. Such 'breached cones' are well seen in Auvergne.

When the activity of a volcano is long-continued it will eventually build up a very large cone, and these large cones are usually composed of both fragmentary material and lava; in a few cases, however, they consist of lava with little or no admixture of ashy matter. Most of the great volcanoes of the world belong to the former class, and their eruptive processes include both explosions of gas and vapours, and the upwelling of lava. Good examples of such cones built up by often-repeated eruptions are afforded by the great volcanoes of the Andes, the highest volcanic mountains of the world. Their structure is usually very simple, and many are so high that in their later stages lava has rarely reached the lip of the crater, and the upper part of the mountain

is chiefly composed of ash. The best European example of a volcano of this type, though on a smaller scale, is Stromboli, which erupts gently every few minutes.

Lava Cones.—A brief reference has already been made to the occurrence in Iceland of cones built up entirely of lava: these afford a very good example of an important class, the basalt cones. Basaltic lava, being poor in silica and rich in magnesia and iron, is very fluid at temperatures only a little above its freezing point and therefore can flow a long way on a quite gentle slope. Consequently basalt cones usually have large diameters in proportion to their height and a smooth outline: they are often called *shield-volcanoes*. However, they possess a well-defined and often very large crater. It is now believed that at any rate a considerable part of the Tertiary basalt lavas of Ireland and Scotland once formed part of great shield-volcanoes. Till recently it was considered that the giant volcanoes of Hawaii, Mauna Kea and Mauna Loa, both nearly 14,000 feet high, were simple shield-volcanoes of extra size, but it is now believed that Mauna Loa, which is still active, is really a pile of separate shields, the centre of activity having shifted in a definite direction, burying the earlier cones and craters. One member of the pile still maintains an independent existence as the great crater of Kilauea, with its lake of fire. The slope of a shield-volcano may be not more than 5°, with a diameter of 20 or 30 miles at the base. The crater of Mauna Loa is about 3 miles across, and that of Kilauea is even larger.

On the other hand lavas with a high silica percentage, especially if combined with high alkalis, are extremely viscous, like treacle or tar, and these will evidently flow for short distances only: they tend to form rounded or dome-like forms and in many instances no crater is visible. This form is very conspicuous in the Puy de Sarcoui in the Auvergne district (Plate XXVI).

Vesuvius.—The history and structure of most great volcanoes is not so simple as this. As is well known, many of them have long periods of quiescence, frequently succeeded by eruptions of great violence. In fact, it may be taken as a general rule that the longer the period between two eruptions, the more violent will be the eruption when it does occur. This is well illustrated by the history of Vesuvius since the beginning of the Christian era.

Before this time the general appearance of the mountain must have been very different from what it is at the present day. It consisted of a simple, steep-sided cone with a very large crater, and was apparently extinct (Fig. 80); there appears to have been no record or tradition of an eruption from it, and probably only a few recognised its volcanic nature. In the year A.D. 79, after a series of violent earthquakes, a great explosion occurred, and the towns of Herculaneum and Pompeii, among others, were completely buried by the débris. The

general effect of this great explosion was to blow away a large part of the walls of the crater. Part of the crater-ring was left standing, and now forms the crescent-shaped elevation partly surrounding the modern cone of Vesuvius, known as Monte Somma (Plate XXV (i)). The

FIG. 80.—PROBABLE APPEARANCE OF VESUVIUS BEFORE A.D. 79.

products of this eruption were entirely of a fragmentary character, and no lava was emitted (Fig. 81).

Since that time Vesuvius has been in a state of more or less continuous activity, although the interval between successive eruptions has often been very long. In most cases lava has been discharged as

FIG. 81.—PROBABLE APPEARANCE OF VESUVIUS AFTER THE ERUPTION OF A.D. 79.

well as ashes and dust, and the cumulative effect of all these eruptions has been to build up a newer cone and crater inside the broken ring of Monte Somma (Fig. 82). The general effect of these eruptions has been sometimes constructive and sometimes destructive, and the height and general form of the mountain have undergone considerable modifications.

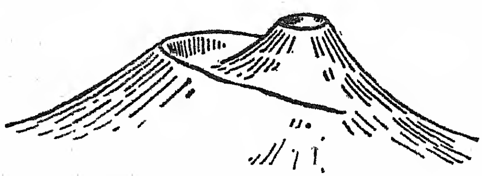
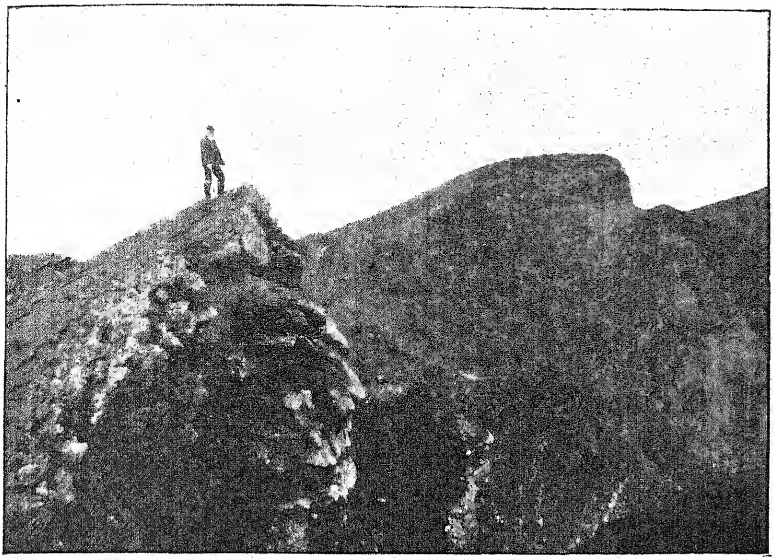


FIG. 82.—DIAGRAMMATIC SKETCH OF THE APPEARANCE OF VESUVIUS IN RECENT TIMES.

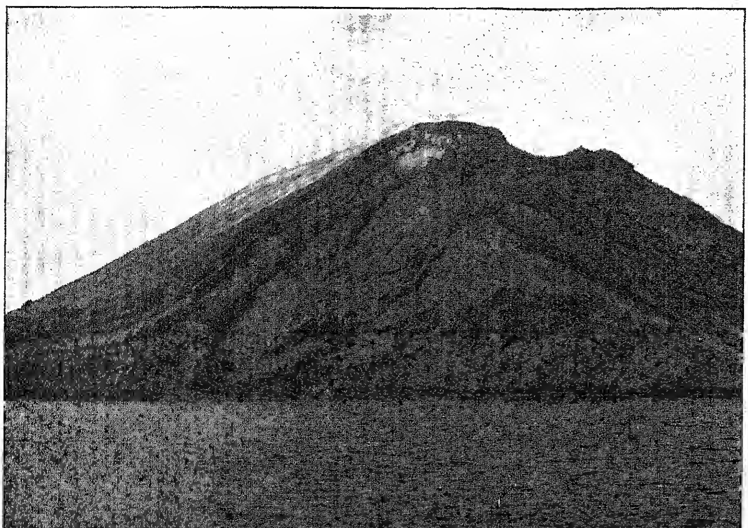
tions. Lava-streams have often issued from cracks in the sides of the cone, and have flowed for long distances, but there has been no change in the position of the main vent.

Paroxysmal Eruptions.—The outburst of A.D. 79 affords a good example of the violent type of explosion which frequently succeeds a long period of quiescence. Several have occurred within recent years,



Tempest Anderson, photo.

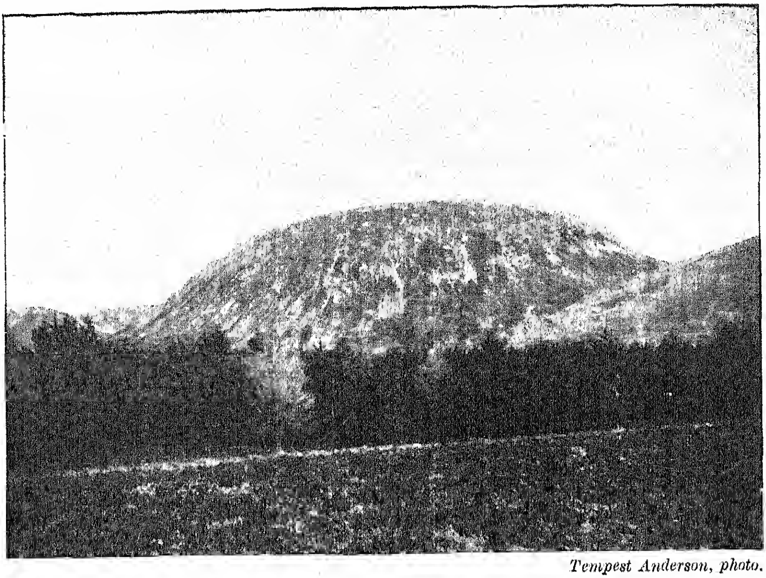
(I) THE EDGE OF THE CRATER: MONTE SOMMA.



Tempest Anderson, photo

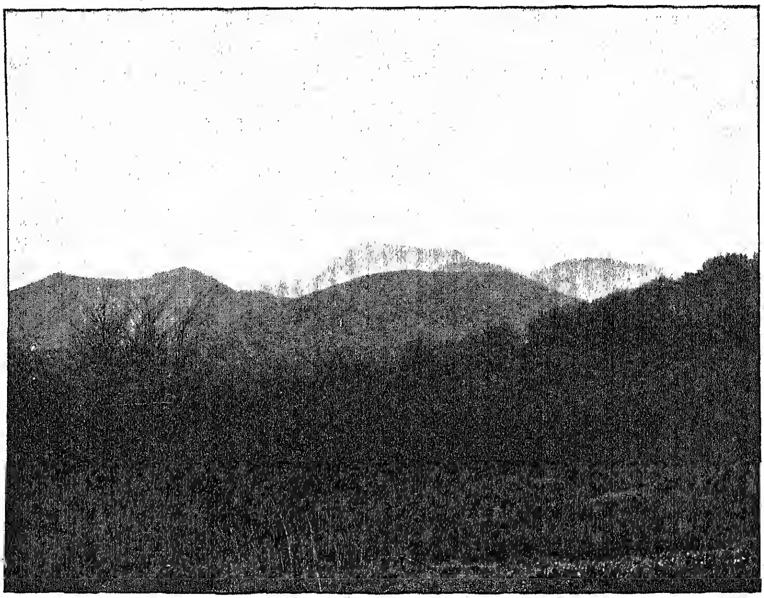
(II) VULCANELLO, FROM THE SEA.

PLATE XXVI



Tempest Anderson, photo.

(I) GRAND SARCOUI, FROM THE WEST: A DOMITIC PUY OF AUVERGNE.



Tempest Anderson, photo.

(II) THE PUYS OF AUVERGNE, FROM THE NORTH.

resulting in the partial or complete destruction of volcanic cones. Thus in the year 1772 the volcano of Papandayang, in Java, was reduced in height by 4,000 feet, and in 1822, in the eruption of Galoongoon, in the same island, a huge hollow was formed in the side of the mountain. Bandai-San, in Japan, had been quiescent for a thousand years till in 1888, without much warning, it blew off its top and one side. Here again there was no lava and no fresh scoria, all the material thrown up consisting of fragments of the existing cone.

Krakatoa.—The most spectacular volcanic episode within living memory was the eruption in 1883, generally known by the name of Krakatoa. This word appears to be in reality a corruption of Rakata. This eruption, whose subsidiary effects were felt in one way or another almost all over the world, was made the subject of a special report by a Committee of the Royal Society, the geological phenomena being

Fig. 83.—Form of Krakatoa in Historic Times.
After the formation of the lateral cone of Rakata and the growth of other cones in the crater.

admirably summarised by Professor Judd, and most of what follows is abstracted from that report.

The island lies in the Straits of Sunda, between Java and Sumatra exactly on the great line of weakness of the Old World, on which are situated so many volcanoes. This line is here crossed by a minor one running north and south and carrying a number of small cones in Java and Sumatra.

The Krakatoa group is a fragment of a great crater-ring, a basal wreck, the result of a great catastrophe of unknown date, slightly modified by later eruptions. Originally about twenty-five miles in circumference at sea-level, and probably 10,000 or 12,000 feet high, it was composed of enstatite-dacite materials resting on post-Tertiary deposits.

The first great explosion formed a crater three or four miles in diameter, which was gradually filled up by eruptions of similar lava from small cones in its interior. The next phase consisted of eruptions of basalt from a lateral vent on the southern lip of the crater-ring; this formed the cone of Rakata, which was 2,623 feet high. There was a gentle eruption from one or more of the smaller central cones in 1680, then quiescence for 200 years (see Fig. 83).

Premonitory earthquakes began in 1878 and gradually increased in violence. At last, on May 20, 1883, moderate activity began: noises were heard 100 miles away and steam rose from the central craters.

This was a Strombolian phase, and increased in force up to August 26. On that day the volcano passed into the paroxysmal or Vesuvian stage. Loud detonations were heard, at first at intervals of ten minutes, but gradually with greater frequency, till they became almost continuous. Professor Judd thought that during this period sea-water was gaining access to the heated magma and cooling the surface of it ; he compared the general effect of this to fastening down the safety valve of a boiler while the fire continues undiminished. The natural consequence followed, and the eruption came to a climax in the form of four explosions of much greater magnitude. As a direct result of these the whole of the northern and lower part of the island disappeared, with the exception of one little patch of rock in the middle, about ten yards square, which is believed to have been originally a dyke or the plug of one of the smaller craters. Half of the cone of Rakata was also blown away,

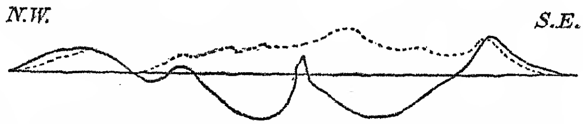


FIG. 84.—OUTLINE OF THE CRATER AS IT IS AT PRESENT.
The dotted line represents the outline before the outburst of August, 1883.

and the geological structure of its inner parts beautifully exposed. About two-thirds of the original area of the island disappeared, and over part of its former site a hollow was formed, in places 1,000 feet deep (Fig. 84). Two new islands were built up, possibly by parasitic cones, but they were soon worn down to sand-banks. The sea-floor within a radius of ten or twelve miles is said to have been raised to an extent varying from 10 to 60 feet, but this was probably due to deposition of material and not to uplift.

Professor Judd gave the following explanation of the causes of the violent explosions in which the eruption culminated. The action in the vent during an eruption is exactly like that in a geyser. The lava is a mass of heated liquid from which large quantities of gas are being disengaged, and these carry up portions of the liquid in which they are entangled. The plugging of a geyser by throwing in turf or other rubbish causes an unusually violent explosion, since it prevents the escape of the steam until a larger quantity has accumulated, which suffices to overcome the extra pressure on the pipe ; so the interruption of regular ejections of the Strombolian type by the chilling of the surface of the lava by access of sea-water caused a check, and then a rally, of the pent-up force of the gas seeking to escape. It is sometimes stated that the water coming in contact with the heated magma was in this case the immediate cause of the great explosions, but it appears only to have acted indirectly in the above-mentioned way.

An enormous amount of solid material was hurled into the air: for many miles around the sea was covered with floating pumice, and even at Batavia, over a hundred miles away, there was so much dust in the air that darkness was complete. Huge sea-waves devastated the shores of Java and Sumatra, causing great loss of life: the sound of the explosions was heard 2,000 miles away and waves of atmospheric disturbance were traced more than once round the world. Several months later fine dust in the air caused extraordinary sunset and afterglow effects even in England.[1]

Basal Wrecks and Calderas.—The general effect of large-scale paroxysmal eruptions is to bring about a great change in the appearance of the volcano: the upper part of the cone is destroyed and the part left takes the form of a wide, more or less circular cavity surrounded by comparatively low walls. What is commonly regarded as the type specimen is the enormous crater, nine miles across, in the island of Palma in the Canaries, known as La Caldera, and this name is applied generically to the whole class. The well-known Peak of Teneriffe in the same island group is a cone 12,000 feet high built up inside an enormous basa wreck. A good small-scale example in Europe is the still feebly active volcanic group of Santorin in the Aegean Archipelago.

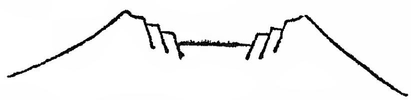


FIG. 85.—SECTION THROUGH A HAWAIIAN VOLCANO, WITH CALDERA.

Calderas, however, are not always formed by explosion in the manner described above. If a great reservoir of molten lava, underlying a cone, should be drawn off through a side fissure instead of through the central vent, as sometimes happens, the upper part of the cone might fall in by its own weight. This process is known as *engulfment*. In this way Dutton and Diller accounted for the formation of Crater Lake, Oregon—a sheet of water measuring six miles by four and occupying a great circular hollow on the top of the Cascade Range. Their chief argument against the explosion theory is the absence from the surrounding country of any fragmentary material which could have formed the upper part of a cone of corresponding height.

The enormous craters of Hawaii are explained as due to slipping and foundering of slices from the walls during rise and fall of molten lava within the vent; but here the process is gradual and not catastrophic.

In the year 1912 Mt. Katmai in Alaska, originally about 7,500 feet high, lost its top during a violently explosive eruption, leaving a caldera $2\frac{1}{2}$ miles across, with cliff-like walls from 2,000 to 3,700 feet high. It is believed that in this instance part at any rate of the original cone

[1] Bonney, *Volcanoes*, 3rd editon. London, 1912, p. 43.

was removed by solution in the newly risen lava. This eruption will be mentioned again later.

Etna.—When the centre of eruption does not remain in the same position throughout the whole history of a volcano, the structure becomes more complex: an instance of this shifting of the centre occurred in the case of Etna. On one side of the cone there is a great hollow or caldera known as the Val del Bove, and its origin is explained as follows. The first eruptions were submarine and of Pliocene age. These built up a cone of moderate size. Presently the chief focus of eruption was shifted to some little distance, and built up a larger cone by which eventually the earlier one was completely buried. The earlier vent after a time again became active, an explosion occurred, and a caldera was formed above it—the present Val del Bove. Later still the second vent, which constitutes the present crater of Etna, again became the outlet for the pent-up forces.

Etna is also remarkable for the large number of secondary cones and craters on its flanks, for there are several hundred within a few miles of the summit. Such secondary vents are a very common feature of the larger volcanoes, and in many cases eruptions, and especially lava-flows, take place from them rather than from the main crater. It is often easier for the lava to find a passage through the sides of the cone instead of mounting to the top, and in some cases these outbreaks take place at a long distance from the summit: for instance, in 1840 a great flow of lava broke out on the flanks of Kilauea at a distance of twenty-seven miles from the crater. These vents, filled with lava, form the dykes which are so conspicuous a feature of most dissected volcanoes.

The Soufrière and Montagne Pelée.—In 1902 two eruptions in the West Indies showed some special features of a type not before recorded, and remarkable for widespread destruction and loss of life. The volcanic chain of the Antilles lies along a folded arc of the Pacific type, the only one on the eastern side of the American continents. Early in May two almost precisely similar eruptions took place within 24 hours in St. Vincent and Martinique, although the two islands are over 60 miles apart.

In the northern part of the island of St. Vincent is a volcano known as the Soufrière, about 4,000 feet high and eight miles in diameter at the base; its summit is occupied by a crater about a mile in diameter, and this before the explosion contained a lake that smelt strongly of sulphuretted hydrogen. (This gas is characteristic of the West Indian volcanic region and soufrières are numerous.) The volcano had been dormant for ninety years, but after preliminary earthquakes during several months, an eruptive phase began on May 6th: on that day the crater lake boiled and overflowed. Next day a remarkable climax was reached in the outburst of a great black cloud of gases and incandescent dust, which rushed down the side of the mountain burning and destroy-

ing everything in its path. Within the area covered by the cloud all vegetation was destroyed and all animals and human beings killed except a few in tightly closed buildings. All descriptions of this eruption make special mention of the electrical effects, and a good deal of destruction of buildings was apparently due to lightning.[1]

The general character of the eruption of Montagne Pelée in Martinique was almost precisely similar, but here the loss of life was very much greater since the black cloud rolled straight down over the town of St. Pierre, which was blotted out of existence and nearly 30,000 of its inhabitants perished.[2] During the next few months on several occasions a *nuée ardente*, as such clouds are named by French geologists, was expelled, and again in 1929 another series occurred: fortunately this time directed towards less thickly populated parts of the island.[3]

The 'Spine' of Montagne Pelée.—At a late stage in the history of the eruption of Montagne Pelée a strange phenomenon occurred. An enormous spine or obelisk (Plate XXVII), protruded itself from the top of the cone of eruption, and eventually reached a height of over 5,000 feet above sea-level, and some 700 feet or more above the summit of the cone. This spine consisted of solidified lava, and it is believed to be the plug of lava which had solidified in the pipe of the volcano at the end of the first phase of the eruption, and was subsequently slowly forced upwards by an increase of pressure from within. The spine very soon lost most of its height owing to ready denudation of the soft material. During the present century a number of structures have been found in various parts of the world probably representing the wrecks of spines of Peléan type.

Black Clouds and Sand-Blasts.—The eruption of Katmai in Alaska in 1912 was accompanied by what seems to have been a variant of the Peléan type of eruption. In this case the sand-blast certainly did not come from the crater of Katmai, but apparently burst through the floor of a valley some miles away, covering it with volcanic ash and pumice to a depth in places of possibly hundreds of feet over several square miles. This was followed by fumarolic action so intense that the region is now called the Valley of Ten Thousand Smokes. It is thought that the cracking of the ground which made possible the outburst of the sand-blast was due either to an enormous intrusion at a small depth or to the breaking up of the roof of a bathylith.

As to the actual cause of such outbursts, to simplify the matter as much as possible, the explanation seems to be that a magma of intermediate to acid composition somehow works itself up into a state of unstable equilibrium, when on a slight change of conditions it suddenly becomes intensely explosive and turns into a mass of crystals and gases

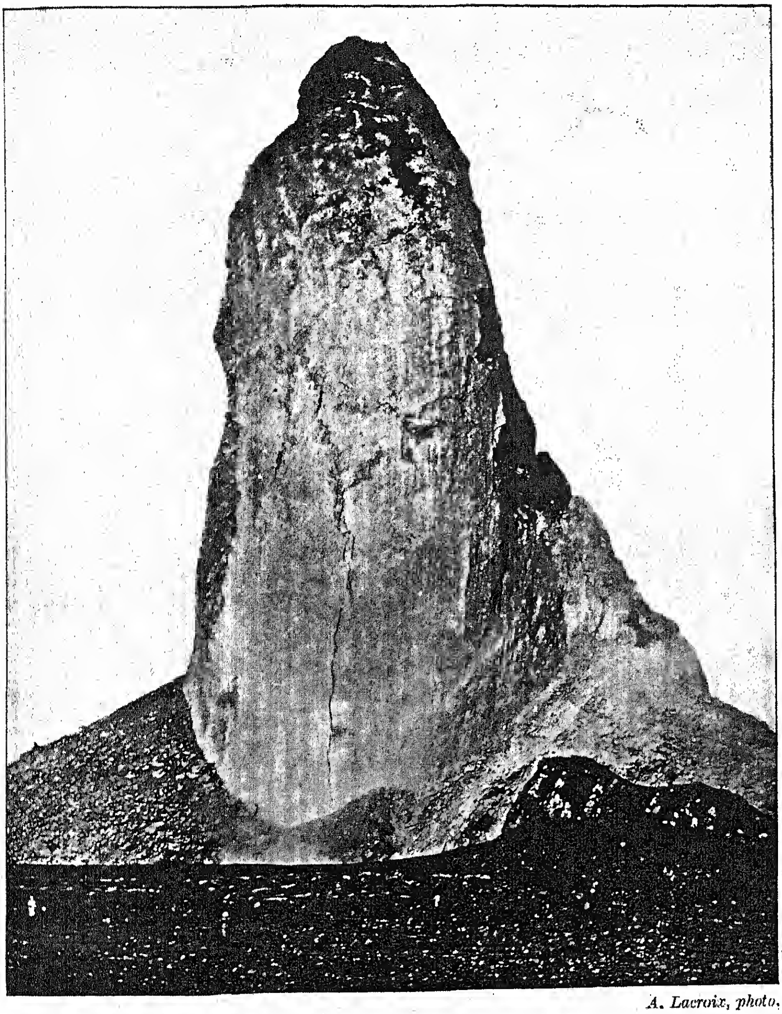
[1] Anderson and Flett, *Phil. Trans. Roy. Soc.*, A. cc, p. 353.
[2] Lacroix, *La Montagne Pelée et ses Eruptions.* Paris, 1904.
[3] Perret, *The Eruption of Mt. Pelée*, 1929–1932. Washington, 1935.

at a very high temperature and pressure: it then bursts out through the weakest spot in its wall or roof as a cloud of red-hot solids suspended in vapour of high density, and rushes down the line of least resistance, behaving in many ways like a dense liquid. The Katmai outburst was at first described as a mud-flow, but a liquid mud-flow could not have been hot enough to burn the trees in the valley, as this one did.[1] The *lahars* of Java, with which it was at first compared, apparently are true mud-flows.

East African Volcanoes.—The development of the Rift Valley system of Eastern Equatorial Africa was accompanied by important volcanic phenomena, apparently spread over a long period of time, but now nearly extinct. In this instance the connexion between tectonic processes and vulcanicity is specially clear. Remains of volcanoes are found in all stages of denudation. The peak of Kenya, 17,040 feet, and one of the summits of Kilimanjaro, 19,320 feet, the highest mountains of Africa, are plugs of a plutonic rock, nepheline-syenite, consolidated at a considerable depth, thus showing that these mountains were once several thousand feet higher than they now are. The second peak of Kilimanjaro has a well-preserved summit crater, now filled with ice and snow. Contrary to a very common belief the Ruwenzori range, 16,800 feet, is not volcanic, but a horst of ancient rocks. The development of the Bufumbiro chain of volcanoes, highest point 14,630 feet, which are probably what Ptolemy described as the Mountains of the Moon, had some highly important effects on the river system of that part of Africa. One of the best preserved craters in East Africa is Longonot, south of Lake Naivasha, near the Uganda railway; but perhaps the most interesting of all is the group of giant craters in Tanganyika Territory. The largest of these, Ngorongoro, is 14 miles across. They appear to be calderas of engulfment.[2] A notable feature of all this region is the richness of the lavas in alkalis, which finds its extreme expression in deposits of salts, for example the Magadi soda lake, as set forth in the section on chemical deposits (p. 174).

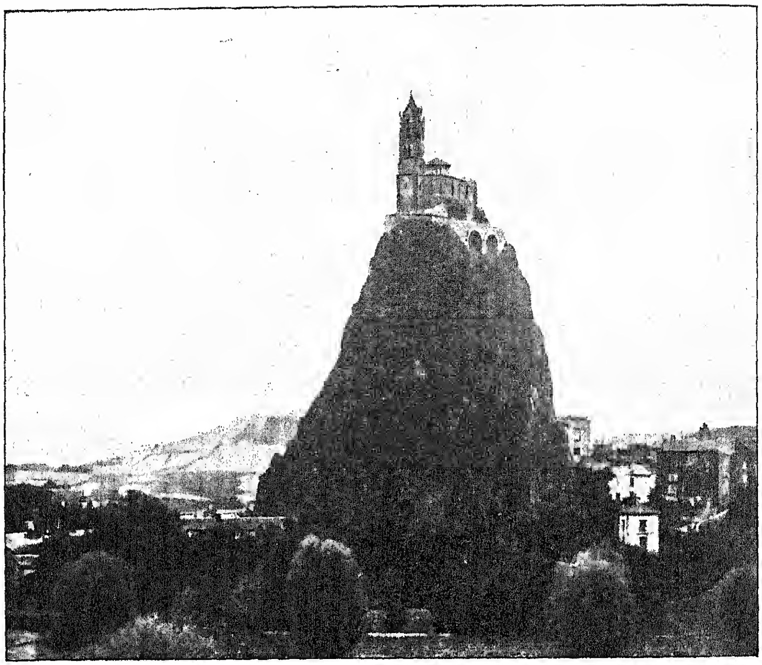
Cauldron Subsidence.—This type of igneous activity is to some extent intermediate between extrusion and intrusion as it gives rise to both surface lavas and ring-dykes. In many cases the former have been removed by denudation, leaving only the latter as evidence. The clearest case in which both are present is the great cauldron subsidence of Glencoe in Scotland. The finest mountain peaks of that district are carved out of a mass of Old Red Sandstone lavas, about 9 miles by 5 miles, surrounded by metamorphic rocks of the Highland Series or by granites. Below the lavas come Highland schists, and forming a ring round the periphery and partly intrusive into the schists and

[1] Fenner, *Journ. of Geol.*, xxviii, 1920, p. 569.
[2] Gregory, *The Rift Valleys and Geology of East Africa.* London, 1921.



A. Lacroix, photo.

THE 'SPINE' OF MONTAGNE PELÉE.



Tempest Anderson, photo.

(I) ROCHER SAINT MICHEL, VELAY: A NECK OF VOLCANIC AGGLOMERATE.

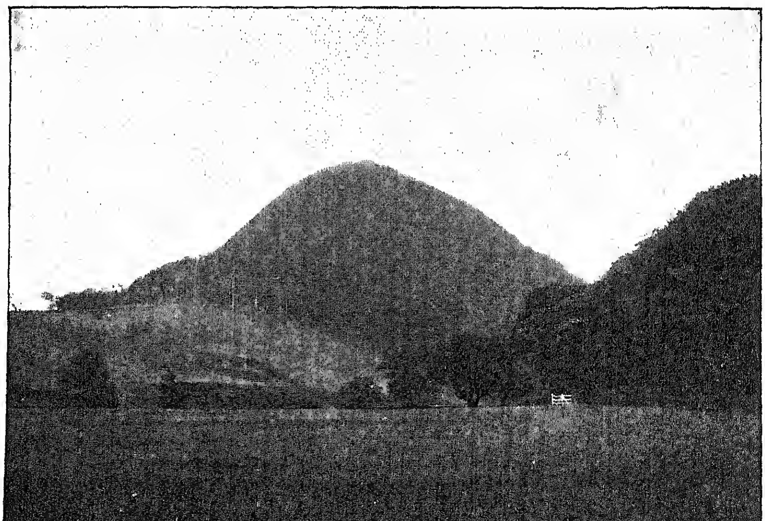


Photo by H.M. Geological Survey.

(II) NORTH BERWICK LAW, HADDINGTONSHIRE: A TRACHYTE PLUG.

lavas are masses of granite rocks. The structure and process of formation are hard to describe in a few words, but can be visualised most easily by the analogy of a rather loosely fitting cork being forced down into a full bottle, the liquid squeezing itself up round the sides. The lavas were first erupted in a normal manner from one or more craters, of which no traces are left: after a while pressure slacked off below, an oval ring-fault was formed and the mass inside it sank down by its own weight, probably for several thousand feet. The heated and still liquid magma was squeezed up the fault fissure, solidifying as granitic rocks of two or three types in successive stages, forming eventually an irregular ring with many offshoots. The process was accompanied by a very extensive dyke-swarm, following the N.E.–S.W. strike of the Highland schists.[1] The same kind of thing occurred in some of the Scottish Tertiary volcanic centres, and has also been described from Iceland. This is one way in which a caldera of engulfment can be formed. In the case of Glencoe the caldera must have been far above the present surface, and no lavas now exist outside the ring-fault.

Structure of Volcanoes.—A typical volcano consists of a more or less conical hill or mountain, called the cone, with a basin-shaped hollow at the top, called the crater. The crater is in direct communication with, and a continuation of, the pipe or vent forming the channel of communication between the heated interior of the earth and the surface.

The internal structure of the cone cannot usually be examined in detail in active volcanoes. It can be most effectively studied in extinct examples in many parts of the world among older rock-formations, which have had their structure laid bare by denudation. They may be found in all stages of dissection—from nearly perfect cones with craters still remaining, down to mere stumps, whose true nature is not at all obvious. Among the older strata, in many cases, all that is left is the plug of igneous rock filling the original channel of eruption, that is, a 'neck': examples are abundant in Britain (see Plate XXVIII). These show that the channel of eruption is usually cylindrical in form, and often passes through the stratified rocks without much disturbance, except that, owing to contraction on cooling of the material in the pipe, the surrounding strata are often dragged down towards the neck, so that for a short distance around all the dips are towards it (see Fig. 3, p. 14).

The cone may be built up of fragmental material only, of lava only, or more commonly of a mixture of the two; and the structure depends upon the composition. The simplest of all is a cinder cone, such as Monte Nuovo or many of those of Auvergne. The material, as it is ejected from the pipe, describes parabolic curves in the air, and falls at a certain distance from the vent, according to its weight: at a

[1] Clough, Maufe and Bailey, *Quart. Jour. Geol. Soc.*, **lxv**, 1909, p. 611.

certain distance from the orifice the deposit will reach a maximum, so that the material gradually accumulates in the form of a ring with slopes towards and away from the centre ; on this, as the cone increases in height, new material will be deposited in inclined layers, dipping both outwards and inwards, a good deal of that which falls on the inner slopes rolling back into the vent, to be again ejected ; and thus the cone is gradually built up with the quaquaversal dip which so sorely puzzled the earlier writers on volcanoes, and led to the long-since abandoned elevation-crater hypothesis, that volcanoes were formed by upheaval ; that they were, in fact, gigantic blisters on the earth's surface. The chief evidence in support of it was the structure of cones with their outward and often steep dip in all directions from the centre.

The addition of flows of lava to fragmental material does not essentially alter the type of structure. If the molten rock rises to the lip of the crater and overflows, it forms sheets intercalated with the ash and having the same angle of dip. In the case of large volcanoes, however, it is much more common for the lava to find its way out through cracks and fissures in the sides or near the base of the cone. These cracks and fissures must be regarded as branches of the main vent, and if they are on a fairly large scale they give rise to subsidiary cones and craters, which introduce great complications into the structure. These fissures may take the form of vertical cracks, and when filled with solidified lava and exposed by denudation they form dykes, intersecting the stratified material and forming a kind of strengthening network or skeleton for the cone. Dykes may extend in a radial form for long distances from centres of eruption, and although technically intrusive they are essentially volcanic, and often approach much more closely to the lavas than to the intrusive rocks in their petrological characters.

Conês built up entirely of lava-flows vary much in structure according to the temperature and degree of viscosity of the lava. This question has already been dealt with in describing the lava-cones of Auvergne, Iceland and Hawaii, and does not require further discussion. Enough has also been said as to the modifications produced by paroxysmal explosions, engulfments and other factors tending to modify the form and destroy the symmetry of volcanic cones.

Dormant and Extinct Volcanoes.—Hitherto we have described chiefly volcanoes known to be in periodical activity, although the intervals between successive eruptions are sometimes very long. There are, however, many volcanoes of which no eruptions have been recorded within historic times, although there may be reason to believe that the volcanic forces are only temporarily quiescent. Such volcanoes are usually spoken of as dormant. Doubtless some of them will again show activity, and this perhaps of a violent nature, since many of the most destructive eruptions of recent years have taken place from volcanoes

which had long been at rest. Again, there are numerous examples of volcanoes which have been quiet so long that they may be safely regarded as extinct. Such extinct volcanoes may either preserve their original form comparatively unchanged, like many of the cones and craters of Auvergne, some of which look as fresh as if they had been formed within the last hundred years, or they may have undergone so much denudation that their original character is masked, and can only be made out by close study. It may be noted in passing that a large part of our knowledge of the internal structure of volcanic cones is necessarily derived from an examination of extinct specimens which have been dissected by erosion and their inner parts laid bare. In particular, it is obviously impossible to study the vent or channel of eruption in living examples, while it is easy to do so if the cone and crater have been removed and the underlying parts exposed. It is only rarely, as in the case of the subsidiary cone of Rakata, that we get a clean section formed by the blowing away of a part of the cone. No actual example of a crater now exists in the British Isles, but dissected volcanoes are abundant, and there is clear evidence of the existence of vulcanicity on the largest scale within this area at many periods of its past history. Much will be said on this subject in subsequent chapters.

The Solfatara Stage.—In the intervals between their eruptions many volcanoes give off steam and various gases from their principal craters and minor openings, and during their decadence these are the only products emitted. They are of various kinds, and the nature of the gas given off serves as an indication of the degree of extinction of the volcano. A very good example of a volcano in this stage is afforded by the large crater known as the Solfatara in the Phlegraean Fields, near Naples. This may be now considered as approaching extinction, since the last recorded eruption occurred in A.D. 1198, when a flow of trachyte was given out. The crater is very wide, and is surrounded by walls only about 100 feet high. The floor is salt and marshy, with here and there a little pool of boiling water. At the foot of the wall on one side is a small opening called the Bocca, and from above this a jet of steam rises to a height of 6 or 7 yards.

Similar jets of steam, together with other gases, are very common in many dormant and decadent volcanoes. Such volcanoes are said to be in the Solfatara stage, which may be regarded as an indication of approaching extinction. Vents in the Solfatara stage are numerous in most of the great volcanic districts of the world, such as Iceland, Java, New Zealand and the Andes.

The most striking example of solfataric action in modern times, and the most carefully investigated, followed the eruption of Katmai in 1912. As previously stated, the Valley of Ten Thousand Smokes is some miles from the crater of Katmai, and was the scene of a sand-blast

through fissures. The steam and gases were evolved from or through the so-called tuff; that is, the material of the sand-blast, partly from small craters, and partly from fissures or mere cracks, the steam-vents being in places arranged in lines a mile or more long. Even in 1929, seventeen years after the eruption, the amount of steam given out was estimated at 26,000,000 litres per second. The nature of the other gases present will be described later. The temperatures in different vents varied greatly: some were below the boiling-point of water, others much higher, the maximum observed being 645° C.[1]

Products of Solfataric Eruptions.—Besides steam, solfataric vents frequently give off other gases, such as hydrochloric acid, sulphur dioxide, sulphuretted hydrogen, ammonium chloride, carbon dioxide, etc. The evolution of these chemically active gases frequently leads to deposition of peculiar minerals round the openings, and causes great alteration of the surrounding rocks. Lavas and ashes are attacked by the acids and lose some of their constituents, so that the whole crumbles to a white powdery mass. This form of alteration can be well seen at Vulcano, and in many districts special names have been applied to rocks which are really nothing but ordinary lavas altered in this way by chemical action.

The gases given off in these circumstances have frequently been collected and examined, and the following classification has been proposed: those in which acid gases are dominant are called Solfataras, those which give off chiefly steam are Fumaroles, and those in which carbon dioxide is the principal product are Mofettes. These may be regarded as three successive stages.

This principle was somewhat extended by St. Claire Deville, who found that the kind of gas evolved depends on the temperature, which is, of course, also a measure of the degree of extinction. He distinguished the following different types:—

1. Dry fumaroles, without steam; these give off, chiefly, anhydrous chlorides at a temperature above 350° C.
2. Acid fumaroles, hydrochloric acid and sulphur dioxide, with some steam, at temperatures above 100° C.
3. Alkaline fumaroles, giving off steam and ammonium chloride at about 100° C.
4. Cold fumaroles, nearly pure water vapour, below 100° C.
5. Mofettes, giving off carbon dioxide, nitrogen and oxygen at the temperature of the atmosphere.

The Valley of Ten Thousand Smokes does not fit very well into this classification. Although 99 per cent. of the gas evolved is steam, with only 0·117 per cent. of hydrochloric acid, the total output was so enormous that this minute percentage sums up to 1,250,000 tons HCl per annum, with 200,000 tons of HF. Nitrogen, sulphuretted hydrogen,

[1] Zies, *The Valley of Ten Thousand Smokes*. National Geographic Society, Washington, 1929; Fenner, *Journ. of Geol.*, xxviii, 1920.

carbon dioxide and methane were also present, and minerals deposited in the solid form include notable amounts of sulphur, pyrite and ammonium chloride, together with many compounds of metals. All this has an important bearing on problems of underground ore-formation, as will appear in Chapter XIII.

In some of the Italian fumaroles, which are also known as *soffioni*, boric acid occurs as a special product, and its extraction has given rise to a considerable industry in Tuscany.

As an example of a mofette or source of carbon dioxide, we may mention the celebrated Grotto del Cane, near Lago d'Agnano, in the Phlegraean Fields—a small cave with a floor sloping downwards away from the entrance, with an accumulation of carbon dioxide, which is heavier than air, at its end. The existence of this gas is demonstrated by lowering a dog into it: the animal rapidly becomes unconscious, but before life is extinct it is extracted and revived with cold water, to repeat the performance for the benefit of the next batch of tourists. A similar cave exists near Royat in Auvergne, and the so-called Upas Valley of Java appears to owe its deadly properties to a layer of the same gas at the bottom. Probably something of this nature gave rise to the old myth of Lake Avernus, over which it was said no bird could fly. Lago d'Averno certainly is a crater-lake, and it is possible that in the early days of man's habitation of Southern Italy it gave out gaseous exhalations of some kind.

Similar emanations of carbon dioxide are very common in the old volcanic districts of Central Germany and Bohemia, and must be regarded as the last traces of the once great activity characterising that region in early Tertiary times. Closely related to them are the many varieties of effervescent and mineral springs also found in many old volcanic districts.

Geysers and Mud-volcanoes.—In some parts of the world there occurs a peculiar type of eruption in which the principal product is not molten rock but water, which, however, is at a high temperature. Two types of these eruptions are usually distinguished: those in which clear water is the sole product are called *Geysers*, and those in which the water contains a considerable amount of solid matter in suspension are called *Mud-volcanoes*, but the two are essentially alike. The mud is derived from the surrounding rocks, and may be regarded as merely an accessory constituent, of no importance. The mud-volcanoes of Paterno, in Sicily, are of special interest, because they occur along the line of the great fissure which runs in a S.S.W.–N.N.E. direction through Etna and the Lipari group. The mud-volcanoes of Krafla, in Iceland, are also well known. They consist of boiling pools of thick black mud, the level of which rises and falls intermittently: they are simply very dirty geysers.

The so-called mud-volcanoes of the Caspian, the Crimea and Burma

are due to escape of gas from oil-deposits, and are not in any sense volcanic.

Geysers may be regarded as the paroxysmal phase of hot springs; at intervals they erupt, and throw a column of hot water and steam high in the air; then they remain quiescent for a certain interval of time, when the process is repeated.

The best-known examples of geysers occur in Iceland, the Yellowstone Park and New Zealand, all of which are regions of decadent volcanic activity. The volcanoes of the Yellowstone Park region are extinct, while those of the other two districts are probably approaching that stage. In its origin and mode of action a geyser is precisely similar to a volcano, and the resemblance goes so far that geysers even build up a cone and crater on a small scale from material deposited from solution, as will be explained subsequently.

One of the best examples is the Great Geyser of Iceland, which gives its name to a whole class. It lies in a plain north-west of Hekla, at the foot of Barnafell. Around the opening is a low cone, about 13 feet high and 120 feet in diameter. At the top of this is a basin about 5 feet deep and 60 feet in diameter. In the middle of this basin is the opening of the pipe, which has a diameter of about 16 feet, with smooth cylindrical and vertical walls. This pipe and basin are ordinarily filled with still clear water at a temperature of from 75° to 90° C. At a depth of 100 feet in the pipe the temperature is about 130°, so that even close to the surface the water is considerably superheated. About every twenty-four hours an eruption occurs, and the water in the basin is thrown up into the air to a height of nearly 200 feet, together with great clouds of steam. The other geysers of Iceland and the districts named show similar phenomena, and do not need separate description.

The explanation of geyser eruptions is simple but of great importance, since it throws light on the origin of ordinary volcanic eruptions. We have seen that at a depth of only 100 feet the water is at a temperature much higher than its boiling-point under atmospheric pressure, hence at greater depths it must be under high pressure. As the temperature increases the vapour tension of the water also increases, till eventually a point is reached when the tension of the vapour exceeds the pressure due to the column of water above; the water at this point passes suddenly into steam, which, on expanding, raises the column, causing an overflow of water at the surface. This diminution of pressure allows the superheated water to flash into steam, which blows out the whole column and causes the eruption.

Classification of Volcanoes.—From the examples of volcanoes and their attendant phenomena described above, it will be seen that a good deal of variation is exhibited. The differences are of two kinds: first of all, actual and fundamental structural variations, as will be seen by a comparison of the fissure-eruptions of the Snake River

plains with gigantic cones like Etna or Cotopaxi; and in the second place, variations due to the fact that all volcanoes are not in the same stage of their life-history; some are embryonic, some in full activity, some decadent, and some dormant or extinct. The examples here described in some detail have been chosen so as to illustrate as much as possible these different phases and stages of vulcanicity. The following table exhibits in a greatly condensed form a summary of the results, it being, of course, understood that examples could be multiplied to any extent, and that no hard-and-fast lines can be drawn between the different groups, since all are connected by transitional forms:—

Active Phase.

Linear Vents.

Fissure eruptions . .	Cracks in the crust, from which lava flows without explosion.
Icelandic type. . .	Very similar to above, but with more explosive action.

Localised Vents.

Explosion pipes . .	Circular vents, produced by single explosion. Ex. Maare of Eifel, Diamond-pipes of South Africa.
Fragmental cones of single eruption.	Ex. Monte Nuovo.

Cones of repeated eruption—non-paroxysmal—
a. Fragmental material only. Ex. Fuji-San.
b. Fragmental material and lava. Ex. Stromboli, Andes.
c. Lava only. Ex. Kilauea, Hawaii; Puy Sarcoui, Auvergne.

Cones of repeated eruption—paroxysmal—
Cones of lava and fragmental material, often with calderas. Ex. Vesuvius, Etna, Krakatoa, Bandai-San, Soufrière.

Stages of Decadence.

a. Solfatara stage.
b. Fumarole stage.
c. Stage of geysers and mud-volcanoes.
d. Stage of hot springs.
e. Stage of effervescent springs and mofettes.

The Distribution of Volcanoes.—Volcanoes are not scattered at random over all parts of the earth's surface, but their distribution shows certain well-marked features. It has long been noticed that practically the whole of them occur within a comparatively short distance from the sea, or from some large sheet of water. Some of the East African volcanoes, such as Kilimanjaro and Kenya, are at a considerable distance from the sea, but they are situated on an important line of fracture, the Great Rift Valley, and close to the African Lakes, so that in this case the exception is apparent rather than real. So far as we know, the same rule applies to the volcanoes of the past, and indeed there is abundant evidence to show that many of the most

important outbreaks of the earlier geological periods were either submarine or situated close to shore-lines, since abundant remains of sea-creatures are found embedded in their ashes and tuffs.

A detailed examination of the distribution in space of existing volcanoes, either active, dormant or recently extinct, reveals some interesting features. They show a very well-marked tendency to arrange themselves in lines parallel to the shores of the continents, and in particular they form an almost complete girdle surrounding the Pacific Ocean, often spoken of as the 'Pacific Ring of Fire.' Starting from the N.W. end of the island of Sumatra, a line of more or less active volcanoes can be traced through Java, the Moluccas, the Philippine Islands, Formosa, Japan, the Kurile Islands, Kamchatka, the Aleutian Islands and Alaska. In British North America and in the United States there are no active volcanoes, but we find plenty of evidence for their existence in a (geologically) very recent period. Some of the highest peaks of Western America still possess well-formed craters, which have undergone but little denudation.[1] In Mexico and Central America active vents are again common, and the line is continued by the chain of great volcanic peaks of the Andes as far as the southern extremity of the continent, and is probably prolonged into the islands of the Antarctic. Thus the coast-line of the Pacific forms the great volcanic region of the globe, in comparison with which all others seem insignificant. The most salient fact arising from a study of this distribution is the coincidence of these lines of vents with the curved arcs indicating the folded chains bounding the Pacific, a coincidence in entire harmony with the views already put forward as to the fundamental connexion between earth-movements and igneous activity.

Turning now to the Atlantic region, we find that volcanoes are much less abundant, and their distribution is less conspicuously regular. Active volcanoes are rare on the Atlantic seaboard, though more common in the oceanic islands. In some districts, however, extensive vulcanicity existed during geologically recent times. During the early part of the Tertiary period North-western Europe was the scene of eruptions on a large scale, and the products of these eruptions form thick beds of basalt in many of the Arctic Islands, Iceland, the Faroes, the Inner Hebrides, and the north-east of Ireland. The modern volcanoes of Iceland must be regarded as the direct descendants of these Tertiary vents. The recently extinct craters of Auvergne are situated at no great distance from the Atlantic. Most of the oceanic islands of the eastern Atlantic are wholly of volcanic origin, and there are a few recently extinct or dormant craters on the west coast of Africa. As before mentioned, there is an important series of volcanoes and igneous

[1] There was a slight eruption from Lassen Peak, in northern California, in August, 1914.

rocks along the line of the Great Rift Valley, even so far north as Palestine.

The volcanoes of the Mediterranean region, and in particular those of the Tyrrhenian group, must be regarded as a survival of the volcanic activity which accompanied the great mountain-building movements of Tertiary times; and in many districts on both sides of the Alpine chain, using the term in its broadest sense, we find abundant relics of great Tertiary and post-Tertiary eruptions, particularly in Central Germany and Bohemia on the northern side of the chain, and in Hungary on the southern side.

Turning now to the western side of the great Atlantic basin, we find the distribution of volcanoes to be of striking simplicity. They are, with one conspicuous exception, entirely absent from the Atlantic coasts of the two Americas; but a line of volcanic vents follows the curved arc of the Antilles, the sole example of a folded chain of Pacific type forming part of the western boundary of the Atlantic.

The facts here briefly summarised as to the geographical distribution of volcanoes may be regarded as the expression of a general law, namely, that vulcanicity accompanies the Pacific type of coast-line, and is absent from the Atlantic type.

Causes of Vulcanicity.—This is a large and difficult question and in the present state of our knowledge it is inadvisable to make any dogmatic statements: there are still too many uncertain factors. Up to a certain point the matter is clear: there is no doubt of the close association in space and time of earth movement and igneous activity, both extrusive and intrusive, but it is not always certain which is cause and which is effect. We have also the incontrovertible facts that the interior of the earth is hotter than the crust and that gases, especially steam, play a dominant part in surface vulcanicity. But the origin of the heat is the main problem. It was formerly supposed that the earth started off with an initial supply, which has been and is being continually lost by radiation into space. But the discovery of radioactive disintegration of elements knocked on the head all theories founded on continuous cooling of the earth as a whole; geological evidence indicates that average climate and therefore surface temperature have been much the same since the later Precambrian. It has been supposed that the internal heat of the earth is due to contraction and consequent friction, but this can scarcely account for its concentration in volcanic regions, and in any case there is no proof that the earth is contracting, except the crust, which is obviously crumpled. Again, we have no exact knowledge of the physical state of the different shells shown to exist by earthquake data: on this opinions differ much and the subject is clearly very speculative. The interior of the earth can be shown to possess a high degree of rigidity, and is therefore not liquid, until pressure has been relieved by earth movement or removal of load.

It seems clear that, however it works in detail, the dominant factor is gas pressure at extremely high temperatures and that in all probability the high temperature is due to radio-active disintegration maintaining or even adding to an initial supply.

When we come to consider the actual mechanism of superficial igneous activity, volcanic eruptions in the narrow sense, we are on somewhat firmer ground. As before said, the most conspicuous feature in many cases is the explosive effect of gases under enormously high pressures. But there is obviously a big difference between the comparatively quiet welling up of mobile basalt in a fissure eruption or a shield-volcano on the one hand, and on the other hand the violently explosive paroxysmal eruptions and sand-blasts. The same explanation cannot fit both in detail, though the fundamental principle is probably the same. In many instances it is obvious that earth movements, by producing points or lines of weakness, have paved the way for eruptions, but it is also possible that mere increase of pressure, due to rise of temperature, might eventually lead to an explosion without any preliminary crust movement: to use a simple analogy from a steam-boiler: sometimes the safety valve works properly; sometimes it sticks and the boiler bursts. When the volcanic mechanism works properly, the result is a gentle eruption, like Stromboli; when it sticks a paroxysmal eruption happens.

In the case of intrusions also it is necessary to discriminate. The mode of origin of dykes and sills is fairly obvious and may safely be attributed to movements of liquid magma under gas pressure. In laccoliths and similar masses there has doubtless been actual lifting of the roof. But when we come to consider the emplacement of the larger stocks and especially of bathyliths we are again confronted with an uncertain factor of first class importance: that is, the extent to which the invading magma has been able to incorporate the material originally occupying the space. This is a very controversial question, and it is not yet possible to attempt an answer. It will be necessary to return to this matter when discussing in the next chapter the problem of the separation of originally homogeneous magmas into fractions of different composition.

PLATE XXIX

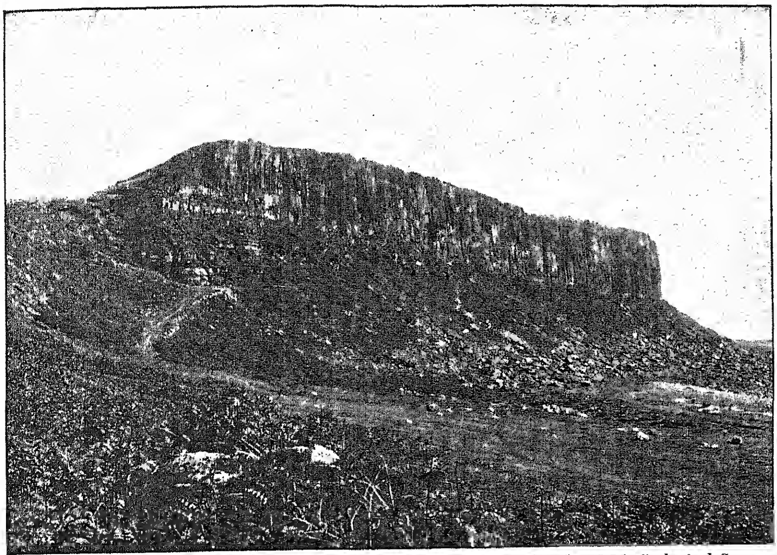


Photo by H.M. Geological Survey.

(I) SILL OF COLUMNAR QUARTZ-PORPHYRY, WITH A SMALL BASALT SILL AND BEDS OF TRIASSIC SANDSTONE AND SHALE BELOW. A RAISED BEACH IN THE FOREGROUND. DRUMADOON, ISLE OF ARRAN.

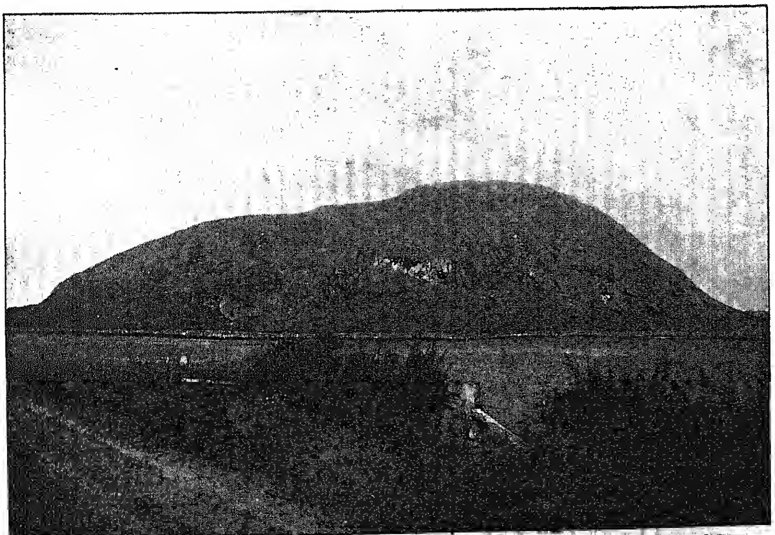


Photo by H.M. Geological Survey.

(II) TRAPRAIN LAW, FROM THE SOUTH. A PHONOLITE LACCOLITH OF CALCIFEROUS SANDSTONE AGE.

PLATE XXX

Photo by H.M. Geological Survey.

TERTIARY BASALT DYKE CUTTING TRIASSIC SANDSTONE. PORT A LEACACH, SOUTH-EAST COAST OF ARRAN. THE DYKE IS TWO FEET BROAD.

CHAPTER XII

THE IGNEOUS AND METAMORPHIC ROCKS

Intrusive Rocks.—Under this heading are included all those rock-masses formed by the solidification of molten material injected into the earth's crust. Hence the form of the intrusion is determined chiefly by two factors, viz. the degree of fluidity of the magma, and the position of the dominant planes of weakness in the rocks into which it is intruded. The distinction between the intrusive and extrusive rocks is somewhat arbitrary since intrusive masses can often be shown to pass into surface lava-flows, and lava-flows must obviously be or have been connected with a subterranean reservoir of molten rock, which is essentially an intrusion. But the division is convenient in practice, and there are certain well-marked physical and structural differences between intrusive and extrusive rocks as a whole.

The Degree of Fluidity of the Magma.—The form of an extrusive flow is determined chiefly by the fluidity of the magma, since, other things being equal, a less viscous magma will flow further and form a thinner sheet than a more viscous one. The degree of fluidity depends partly on the temperature and partly on the chemical composition of the magma; a basic magma forms a highly mobile liquid at a temperature at which an acid one is still very viscous. The most viscous magmas of all appear to be certain sub-acid or intermediate types, rich in alkalis, especially the trachytes and phonolites.

In respect of the intrusive rocks similar considerations apply. A liquid magma possesses a much greater power of penetrating along planes of weakness than a viscous one, and in consequence tends to spread itself out in thin sheets along the bedding planes of the strata, while a viscous magma has little penetrating power, but arches up the strata into a dome-like form over a comparatively small area.

The Influence of Rock-structure on the Form of Intrusions.—Since the form of intrusive masses is to a great extent determined by the arrangement of the dominant planes of weakness in the rocks into which they are intruded, it is evident that the structure of the latter is an important factor in the case. The structures of rocks from this point of view are chiefly dependent on the type of earth-movement to which they have been subjected. As we have already seen, in regions affected by continent-building and plateau-building movements, the rocks remain horizontal or but slightly inclined over large areas, while

in regions of mountain-building movements they are often highly folded, contorted and fractured. It is possible to distinguish two classes of intrusions corresponding to these differences of structure, which may be referred to as intrusions in unfolded and folded areas respectively.

In the first chapter brief definitions have been given of a few of the simpler types of intrusion. At the risk of slight repetition these will now be amplified somewhat.

Intrusions in Unfolded Areas.—Some of the clearest examples of this category are found in the Western States of America, in Colorado, Utah and Wyoming, in connection with the great plateaus of that region. It is to be noted that unfolded areas are often extensively faulted, especially where they have been subjected to tensile stresses, and in such cases the phenomena of intrusion show some analogy to fissure eruptions. The feeders of fissure eruptions if denuded to a sufficient depth must necessarily appear as dykes.

Sheets or Sills.—In this form of intrusion the magma penetrates for considerable distances along the horizontal or inclined bedding planes, so that the lateral extent of the mass is great as compared with its thickness. The 'Palisade Trap' of New Jersey may be selected as a type: this extends over an area of at least 6,000 square miles and attains a maximum thickness of 850 feet. Since it is always well in geology to think to true scale, the actual form of this sheet may be considered a little more closely. Now if 6,000 square miles is represented by a sheet of paper of 60 square inches in area, the thickness of the sheet on the same scale would be one-sixtieth of an inch, about a quarter as thick as a page of this book. This gives a vivid idea of the penetrating power of a mobile magma. A good instance of a similar sheet is found in the Great Whin Sill of the north of England, which extends into five counties: Northumberland, Durham, Yorkshire, Westmorland and Cumberland. It is intrusive into the Lower Carboniferous series over an area of at least 1,500 square miles: how far it extends to the eastward is unknown: it has been found in a deep boring at Crook in Durham, where it is very thick, so it probably extends much further. Its maximum thickness is about 150 feet. It does not occur at one horizon throughout, but is distinctly transgressive. The situation of the feeding channel or channels is not known.

Sills may be of any size, from inches to hundreds of feet in thickness. Some have been filled by a single injection, while in others the process has been repeated; when a sill consists of sheets of more than one kind of rock it is called *composite*. A vertical, often more or less hexagonal columnar structure is common, due to contraction on cooling: however, this is also seen in lava-flows.

Laccoliths.—Many of the intrusions in the plateau region of America and elsewhere take a form to which the name of laccolith has been

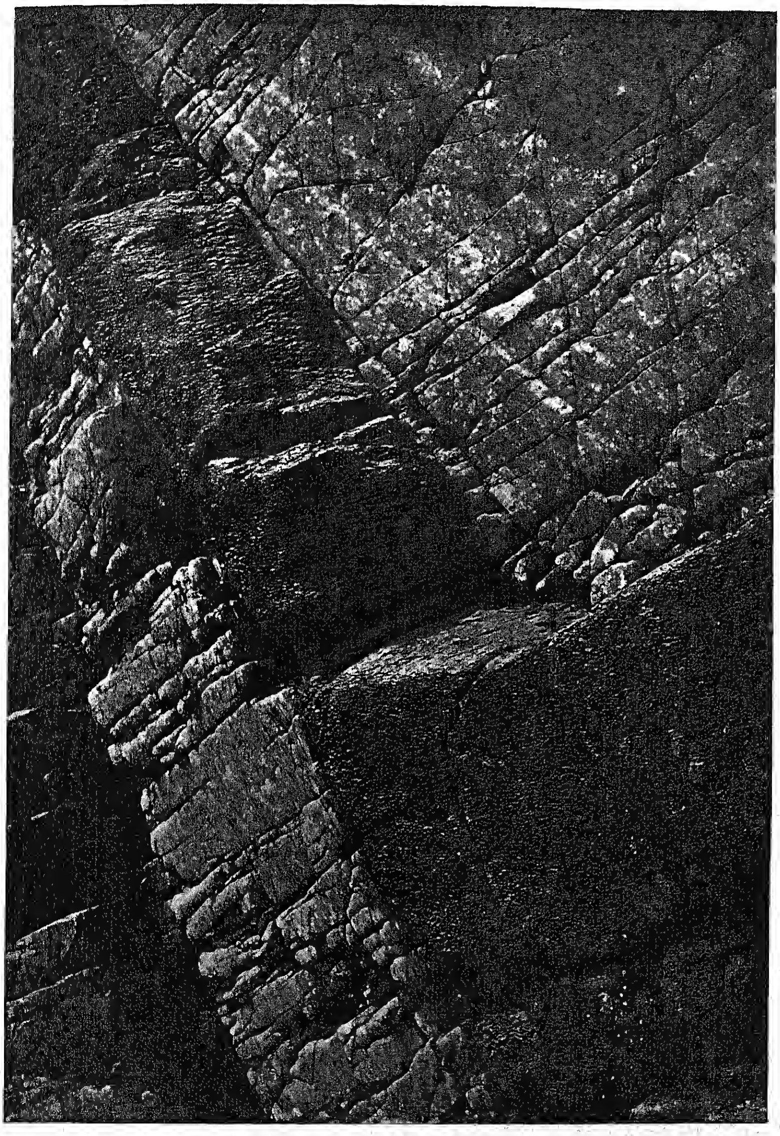


Photo by H.M. Geological Survey.

CLEAVED LAMPROPHYRE DYKE IN GRITS. NORTH SIDE OF KILCHARAR BAY, ISLAY.

PLATE XXXII

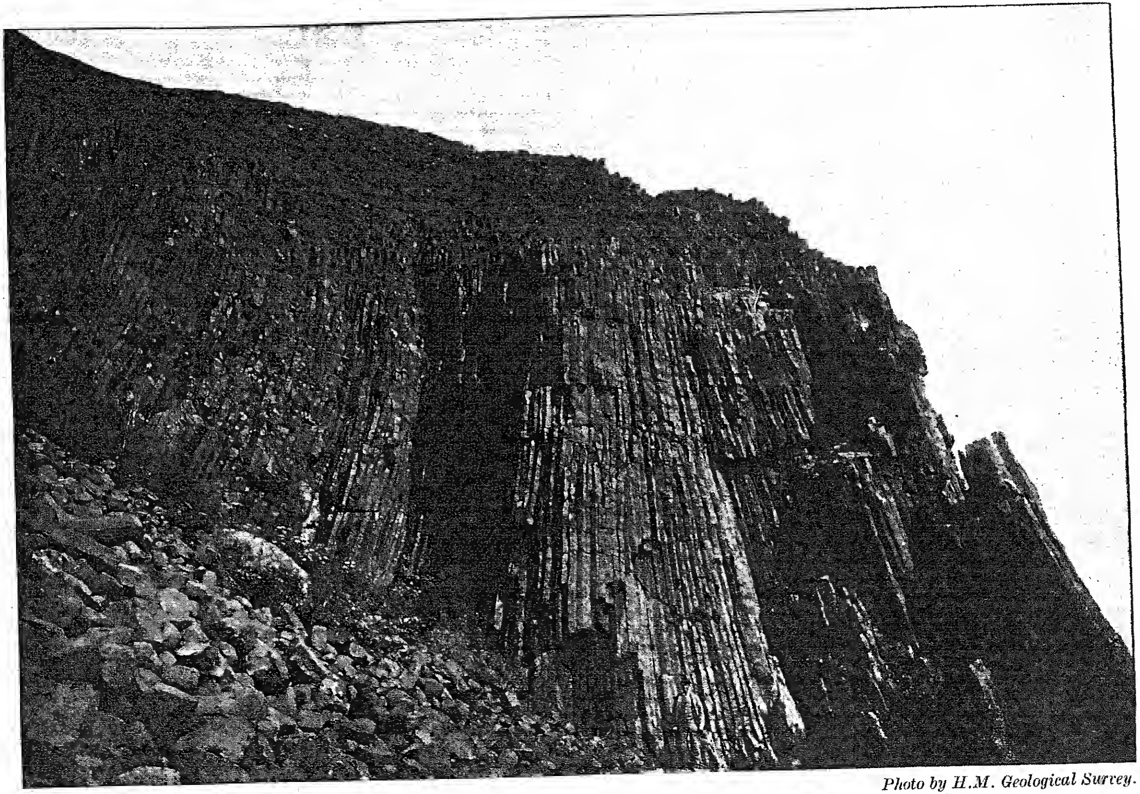


Photo by H.M. Geological Survey.

CLIFF OF COLUMNAR BASALT IN THE TUFF AND AGGLOMERATE OF 'KINCRAIG NECK,' SHOWING RADIATING COLUMNAR STRUCTURE. EAST SIDE OF KINCRAIG POINT, ELIE, FIFESHIRE.

given.[1] In this case the intrusive rock has arched up the overlying strata into the form of a dome, and has itself assumed somewhat the shape of a flat loaf or tea-cake. In some cases, however, the form is more complex than this, since the main mass gives off more or less irregular offshoots, or apophyses, into the surrounding strata (Fig. 1, p. 12). A laccolith often passes at its margin into a sheet or sill, and frequently smaller subsidiary laccoliths are found to be intruded in the region where the bending of the strata around the main laccolith is most pronounced (see Fig. 86).

It appears probable that in these simple cases the whole mass of the

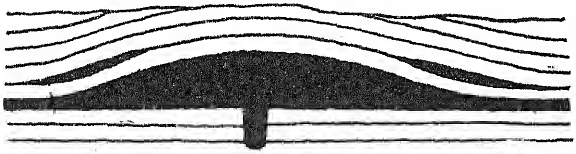


Fig. 86.—Laccolith passing laterally into a Sill, with Minor Laccoliths.

igneous rock has been intruded at one time, but instances are known of intrusions which appear to consist of a series of laccoliths one above the other, the so-called 'cedar-tree' laccolith (Fig. 87). Here it is probable that each projecting portion represents a separate injection of molten magma, and that the whole is due to a succession of intrusions from one common source.

The classical examples of laccoliths are those described by Gilbert in his *Geology of the Henry Mountains*, but a similar structure has since been recognised in many other localities. The great gabbro and

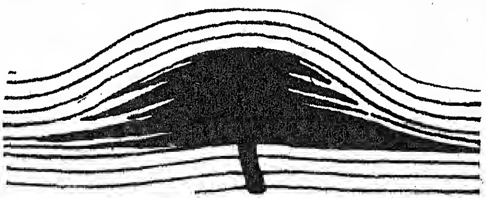


Fig. 87.—'Cedar Tree' Laccolith.

granite intrusions of the Cuillin Hills and Red Hills in Skye are of this nature.[2] In most cases the channels through which the magma rose have not been exposed by denudation and their existence is a matter of inference.

Bysmaliths or Plutonic Plugs.—In the Black Hills of Dakota and some other localities in Western America a peculiar type of intrusion has been described, under the name of Bysmalith or Plutonic Plug. These

[1] Gilbert, *Geology of the Henry Mountains*, p. 19.
[2] Harker, 'The Tertiary Igneous Rocks of Skye,' *Mem. Geol. Survey*, 1904, p. 83.

do not seem to differ in any essential respect from ordinary laccoliths, but they appear to consist of rocks of a still higher degree of viscosity, so that their thickness is greater in comparison with their horizontal extent. One of the best examples is Mt. Holmes, in the Yellowstone Park, described by Iddings (see Fig. 88). Here the amount of vertical dis-

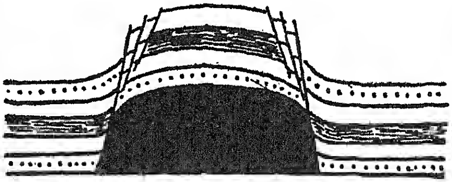


FIG. 88.—BYSMALITH.

placement produced by the intrustion is so great that the overlying rocks have been fractured to a certain extent around the circumference of the igneous mass. The distance to which the plug extends downwards is unknown. Here the mechanism has a close relation to that leading to the formation of ring-dykes (see Chapter I, p. 14). It is the exact reverse of a cauldron subsidence.

Lopoliths.—In some of the largest known intrusions of laccolithic type both upper and lower surfaces are concave upwards, so that the whole mass has a saucer-like form. These are called *lopoliths*. Two well-known examples are the Sudbury intrusion in Ontario, the source of most of the nickel supplies of the world, and the Duluth gabbro at the head of Lake Superior. The largest of all is the great Bushveld igneous complex of the Transvaal, which is 300 miles long and nearly 200 miles wide and contains a remarkable variety of rocks. This type is due to intrusion of magma in a region undergoing depression, probably owing to the rise of the magma itself to higher levels; in the Bushveld at any rate following extensive eruptions of surface lavas.

Minor Intrusions: Dykes and Sills.—Minor intrusions chiefly take the form of thin sheets of rock, either injected along the bedding planes,

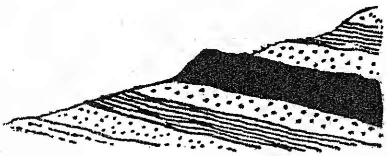


FIG. 89.—INTRUSIVE SILL.

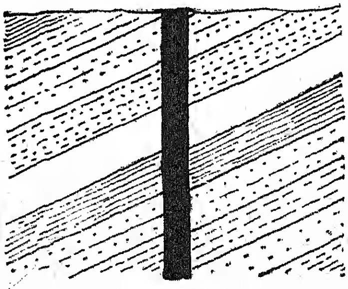


FIG. 90.—DYKE.

forming sills (Fig. 89), differing only in size from the sheets or sills above described, or else across the stratification, when they are spoken of as dykes (Fig. 90 and Plate XXX). The distribution of dykes is generally connected with the intrusion of large plutonic masses, or else they are subsidiary effects of crust-movements on a large scale. In the first case they tend to possess a radial arrangement around the central intrusion, while in the second case they show parallelism over large areas. Such systems of parallel dykes may have served as the channels of fissure-eruptions (see p. 224). Cone sheets and ring-dykes have already been sufficiently defined in the introductory chapter.

Intrusions in Folded Areas.—The forms assumed by masses of intrusive igneous rock in folded regions are naturally less simple and less regular than those just described, since the arrangement of the dominant planes of weakness varies in every case according to local circumstances. Consequently the nomenclature employed cannot be so definite as in the case of unfolded areas. The intrusive magma must necessarily tend to emplace itself in the weaker regions, especially where the rocks are stretched, and will avoid regions of compression. In a series of simple anticlines and synclines, the tops of the anticlines are stretched, while the synclines are compressed. The magma will therefore tend to form saddle-shaped masses of indefinite length on the crests of the anticlines: these are called *phacoliths*. Occasionally an inverted phacolith is found in a syncline.

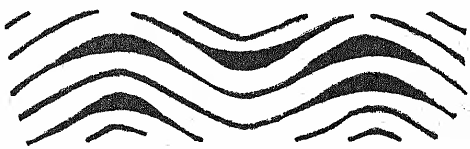


FIG. 91.—PHACOLITHS. (After Harker.)

Beyond this point it is difficult to draw up a precise nomenclature, for two reasons: firstly, because the forms of the intrusions themselves often show little or no regularity but almost infinite variety, and secondly, because many of the terms commonly employed have been used by different writers in vague and sometimes contradictory senses.

Stocks are large masses, often with an area of many square miles, having steeply inclined or even vertical walls. Some of the smaller stocks are certainly volcanic necks, and should be so called if there is proof that they were once the channels of surface eruptions. The larger stocks, which probably did not originally communicate with the surface, may be of any shape in plan, though in many there is a tendency to circularity. As a rule the form does not show much relation to the general rock structure of the district, and it is often very difficult to account for the disappearance of the material originally occupying the

space. Chemical analysis generally shows that it has not been merely melted and recrystallised. Sometimes owing to survival of parts of the roof after incomplete denudation the form of the surface outcrop of a stock appears to be much complicated. Stocks are numerous in nearly all regions of extensive intrusion of granitic rocks: good examples are seen in the Scottish Highlands.

The largest intrusions, nearly always granite, are included under the general name of *bathylith.* There is no downward limit of size, but a continuous gradation from bathyliths to stocks. The typical form is elongated, most commonly extending along the axis of a folded mountain chain. Unlike laccoliths and phacoliths, there is no floor, and the intrusion may extend downwards indefinitely, becoming wider and wider in depth. Some of the greater bathyliths probably merge eventually into a general granitic shell, underlying all the continental blocks: in fact, the sial (see p. 10). The roof is commonly very irregular, and masses of the country rock, often more or less wedge-like in form, may extend downwards into the intrusion, forming *roof-pendants.* There is commonly evidence of more or less extensive melting and incorporation of the roof-rocks. The best example of a simple bathylith in the British Isles is the Leinster granite: this extends for about 70 miles to the south-west of Dublin. In the Malay Peninsula several elongated granite bathyliths striking N.–S. cut across the general N.W.–S.E. trend of the country: the Main Range bathylith, about 300 miles long, with a maximum width of 40 miles, is the site of the most important tin deposits of the world. The largest known intrusion is the Coast Bathylith of British Columbia: at the surface it is 1,100 miles long and from 80 to 120 miles wide. It lies parallel to the main axis of the Rocky Mountains from the United States border to Alaska.

The curiously regular granite masses of Cornwall afford an example of what in America are called *cupolas*; that is, dome-like projections on the upper surface of a bathylith. The Carn Menellis granite forms an almost perfect circle 9 miles in diameter at the surface: some others are larger, though not quite so regular. It is known that granite underlies the slaty rocks in many parts of Cornwall, and it is probably continuous throughout the county and beyond: e.g. the Scilly Isles. The structure of the Dartmoor granite appears to be different and more complicated.

The term *boss* is often used for both stocks and cupolas. It possesses no very precise meaning.

The sheets, sills and dykes in folded areas do not differ in any essential respect from those previously described in unfolded areas, except that they naturally do not generally possess so great a lateral extension. Owing to the complexity of the prevailing structures the terms used cannot be very strictly defined, but, generally speaking, intrusive sheets and masses of rock parallel to the bedding planes are called sills, whereas

those which cut across the bedding planes are dykes. Originally, most sills are more or less horizontal, whereas dykes approach the vertical, but as a result of subsequent movements they may come to be inclined in any position. Besides the foregoing, there are often to be found masses of igneous rock of various sizes which cannot be classified under any definite heading, but are of entirely irregular form. These are mostly of small dimensions.

The Composition and Classification of Igneous Rocks.—In the introductory chapter a short list was given of the chief minerals of the igneous and sedimentary rocks. The sediments have already been dealt with, and it is now necessary to consider in some detail the chemical composition of the material of the igneous rocks before solidification, and the character of the rocks produced by such solidification under different conditions.[1] The term *magma* is now used to express this molten material. Although all natural magmas constitute very complex systems, nevertheless they obey the ordinary laws of physical chemistry and thermodynamics, and in some of the simpler cases a good deal has been done in the way of experimental investigation and synthesis, though the work is difficult owing to the high temperatures involved and the intractable nature of the gas-phases at such temperatures.

The Chemical Constituents of Magmas.—It is probable that all, or nearly all, the known elements are found in igneous rocks, but many of them are exceedingly rare, and only a small number are of any importance. The elements which occur in large amount in igneous rocks, or what may be called the normal constituents of the magma, are the following: oxygen, silicon, aluminium, iron, calcium, magnesium, sodium, and potassium: these form about 99 per cent. of the whole, according to the most trustworthy estimates, obtained by combining a great number of analyses of rocks of all kinds.[2] The following elements are also of almost universal occurrence in small quantities: titanium, hydrogen, carbon, phosphorus, manganese and sulphur. These together form about 0·9 per cent., while the remaining 0·1 per cent. includes the rare constituents.

Instead of regarding the elements as the constituents of the magma, it is found more convenient in practice to consider them as combined with oxygen in the form of oxides: the constituents of the magma can then be arranged in natural groups, characterised by analogous chemical and physical properties; that is to say, the members of each group are isomorphous with one another (except Group V). Such an arrangement is shown in the following table:

[1] Harker, *Petrology for Students*, 7th edition, Cambridge, 1935; Hatch and Wells, *The Petrology of the Igneous Rocks*, 9th edition. London, 1937.

[2] Clarke, *The Data of Geochemistry*, 5th ed.; Bull. 770, *U.S. Geol. Survey*, 1924, p. 29.

I. Silica, SiO_2.
II. Alumina, Al_2O_3; ferric oxide, Fe_2O_3.
III. Magnesia, MgO; ferrous oxide, FeO; lime, CaO.
IV. Potash, K_2O; soda, Na_2O; water, H_2O.
V. The accessory constituents, titanium dioxide, TiO_2; phosphorus pentoxide, P_2O_5; carbon dioxide, CO_2, etc.

It will be observed that in this table iron occurs twice, as the ferrous and ferric oxide; this separation is abundantly justified on chemical grounds, since each of the two oxides forms a series of well-defined compounds, having different physical properties.

From this point of view a fused rock-magma must be regarded as a mutual solution of all or any of these constituents. Consequently, the number of components of such a system is very large, and the whole phenomenon becomes very complex. For practical purposes the accessory constituents (Group V) may usually be disregarded, but even then the solution may contain as many as nine different oxides. Another complication is also introduced by the fact that under certain conditions the whole or part may not form crystalline minerals of definite composition, but may solidify as a homogeneous, amorphous mass, a *glass*. Since such a non-crystalline mass may vary indefinitely in its composition, and is of uniform composition throughout, the chemical composition of such a rock is all we have to rely on in its classification. Crystalline rocks, on the other hand, need not be homogeneous: their composition may vary at different points. This is equivalent to saying that they are composed of an aggregate of crystals of different minerals. Here, then, besides the chemical composition, we require to know also the nature of the minerals present, and the proportion in which each occurs, before we can assign the rock to its proper place in the scheme of classification.

Chemical Characters of Rock Constituents and Magmas.—In the great majority of cases silica is the most abundant constituent, and it very commonly exceeds in amount all the others taken together. The range of silica content in normal rocks is from about 40 to 80 per cent.: in only a few exceptional cases is it above or below these figures. Nearly all the important rock-forming minerals are silicates, or compounds of silica with one or more metallic oxides. In these compounds silica may be regarded as playing the part of an acid, while the metallic oxides act as bases. Hence rocks rich in silica are spoken of as *acid*, and those poor in silica but rich in metallic oxides as *basic*. It will thus be seen that in many respects silica is the most important constituent of a magma, and the proportion in which it is present is of great weight in classification, since the manner in which the basic oxides combine to form minerals is to a great degree controlled by the amount of silica present.

It has been found convenient to represent the chemical composition

of the igneous rocks, and the relationships of the different groups, by means of a diagram, as follows: for abscissae we take the percentage of silica as the dominant constituent, and for ordinates the sum of the percentages of potash and soda. It is obvious that any other constituent or group of constituents could be used in a similar way, but the alkalis are found to give the best results. In such a diagram the composition of any rock, plotted from its analysis, is represented by a point. When a sufficiently large number of analyses of rocks from all parts of the world are plotted in this way, some interesting facts become apparent: the points tend to arrange themselves into two linear

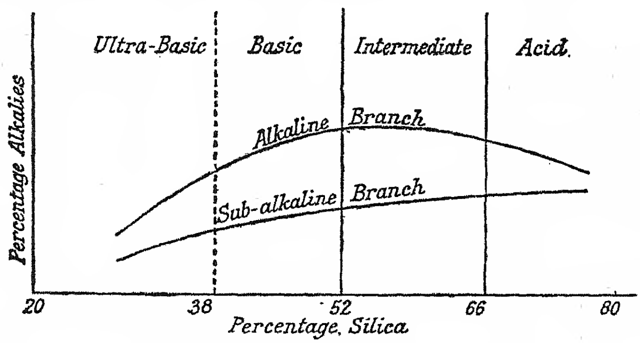


Fig. 92.—Diagram of Igneous Magmas.

groups, having a peculiar arrangement; these linear groups of points can be generalised by drawing curves through them, and these two curves are convex upwards, but one much more so than the other (see Fig. 92). We thus obtain two curves approximating at the ends and diverging most widely in the middle. The first series is now commonly spoken of as the alkali series, and the second as the calc-alkali or sub-alkali series. For this purpose potash and soda alone are considered to be alkalis, whereas lime is not; and indeed it may be said that lime is, in a petrological sense, in opposition to the potash-soda group, since lime characterises the sub-alkaline series.

Petrographical Provinces.—When a sufficiently large number of analyses have been made of the rocks of any given area, it is frequently found that even though there may be a wide range in composition, and especially in silica percentages, nevertheless certain chemical peculiarities run through the whole series. It is also found that the rocks of one area differ in some special manner from the rocks of some other area or areas. Thus, for example, the vast majority of the igneous rocks of Britain belong to the group described in the last section as sub-alkaline, poor in alkalis and rich in lime. The rocks of the New England States, on the other hand, are distinctly alkaline, being characterised by a high alkali-content, and especially by the abundance of soda; other regions

where alkali rocks are specially well developed are Southern Norway, Finland, Portugal and Brazil; while good examples of sub-alkaline regions are Hungary and the Pacific slope of the American continent. Any region thus marked off by special peculiarities is conveniently known as a *petrographical province.*

The occurrence of chemical peculiarities running through all or nearly all the igneous rocks of a province shows that they are not brought together by chance, but that there must be some real relationship between the different types: that is to say, all the rocks of a petrographical province may be referred to some common origin.

Igneous Complexes.—The same conception may also be extended to groups of rocks on a much smaller scale than those referred to in the last section. It is frequently found, when any igneous mass is examined in detail, that there are chemical and mineralogical peculiarities running through a number of rock types composing the whole; in particular there are often to be found in association a variety of rocks differing from one another in detail, and especially in silica percentage, but still resembling one another strongly in other points; such peculiarities may be either chemical, as in the case of petrographical provinces, or mineralogical; that is to say the different rocks possess in common one or more peculiar minerals, or associations of minerals, which serve to indicate relationship, or derivation from a common source. A set of mutually related rocks of this kind, occurring within a comparatively small area, is usually spoken of as forming an *igneous complex.* It is not practicable at this stage to give actual examples of this kind, since to do so would involve an acquaintance with the detailed classification of the igneous rocks generally, but many such are known in Britain and elsewhere.

One petrographical province often includes many igneous complexes, as will be seen in the example now to be described.

The Tertiary Province of North-western Europe.—The British part of this province is perhaps the most complicated and certainly the most thoroughly investigated region of igneous rocks in the world. It is impossible here to give more than the briefest sketch, but fortunately the whole subject has been admirably summarised in an easily accessible and very cheap publication of the Geological Survey,[1] to which the student is referred for a general account. Full details of the Scottish area are set forth in several large official memoirs, suitable for advanced workers. References to all of these will be found in the handbook just quoted.

In the year 1874 Professor Judd published the first comprehensive description on modern lines of the Scottish area, in which he attributed the origin of the basalts and accompanying rocks to giant volcanoes, something like those of Hawaii; while in 1897 Sir Archibald Geikie,

[1] *British Regional Geology,* 'Scotland: The Tertiary Volcanic Districts.' Edinburgh, 1935. Price 1*s.* 6*d.*

who had visited the Snake River Plains in the North-western United States, concluded that the basalts were due to fissure-eruptions. In 1904 the appearance of Dr. Harker's memoir on the south-eastern part of the Isle of Skye drew attention to the important part there played by intrusive types, both plutonic and hypabyssal, thus laying the foundation of all later developments. To cut this historical introduction short, it may be said that the work of the Geological Survey has shown that Judd's interpretation was nearer to the truth, at any rate for the British area, though fissure eruptions are not excluded, for example in Iceland. It is now clear that the subject was too vast to be tackled effectively by any one man, and in reading the earlier literature allowance should be made for this.

As already mentioned Tertiary igneous rocks cover well over 2,000 square miles in the British Isles: of this about two thirds is in Ireland, but although the Giant's Causeway is perhaps the best-known of all examples, to a geologist the Scottish occurrences are the more interesting and instructive. The four principal areas in Scotland, from north to south, are: the Isle of Skye; Ardnamurchan; Mull; Arran: the Isles of Rum and Eigg also show points of special interest.

The first phase in each area was the eruption of basalt flows of wide extent, apparently for the most part forming great shield volcanoes. In Mull there is clear evidence of the formation of a great caldera, 6 miles across, once occupied by a lake. At a later stage, both in Mull and Ardnamurchan, most complicated relations developed, one of the most important features being the intrusion of great series of cone-sheets and ring-dykes, as well as other less regular masses of plutonic type, definitely located around centres. Moreover the positions of the main centres did not always remain constant, some having shifted once or even twice. Throughout the period of activity also swarms of dykes were being intruded, the great majority of them definitely pointing to the plutonic centres. In no case in Scotland has it yet been proved that a dyke was the feeder of a basalt flow. It seems quite clear that the plutonic centres are the denuded cores of a string of giant volcanoes. For the nature of the rocks composing them reference must be made to the publications cited above. Some details concerning the Isle of Skye are given on p. 266 of this book, and further references to the general subject are made in the last chapter.

Solidification of the Magma.—The solidification of a molten rock-magma, whether intrusive or extrusive, must take place in accordance with the physical laws governing the behaviour of solutions. As has been already pointed out, there are three distinct cases to consider: (1) the whole may solidify as a homogeneous mass, a *glass* in the petrographical sense; (2) it may solidify as an aggregate of crystalline minerals; (3) the resulting rock may consist partly of crystals and partly of glass. These differences correspond to the different conditions

under which solidification takes place. Slow cooling favours crystallisation, whereas rapid cooling leads to formation of glass. Now the conditions which produce slow cooling are especially (1) the existence of a large body of molten magma, (2) a thick covering of rock above it. Consequently, large deep-seated masses are always wholly crystalline and generally coarse in texture. Lava-flows, on the other hand, are usually comparatively thin, so that they lose heat quickly, and they are commonly poured out on the surface of the ground. Hence lavas have a strong tendency to solidify as glass, and the same applies to small masses intruded under a thin cover of rock. But here another factor comes into play, since magmas of different chemical composition show varying powers of crystallisation. A high percentage of silica favours formation of glass, consequently many acid lavas are glassy, whereas basic rocks are rarely glassy to any great extent; as a rule basic rock-masses only possess a thin selvage of glass on the surface, or on the edges of small dykes and sills, chilled by contact with cold walls. Large deep-seated masses of any kind often possess a marginal layer of finer texture, but they heat up the surrounding rocks to such an extent that formation of glass is prevented, owing to the slow cooling. The heat-conductivity of rocks is very low.

Since magmas obey the ordinary laws of physical chemistry their relations can be expressed at any rate theoretically in thermal diagrams of the usual kind and in simple cases this is often done. Thus there are igneous rocks consisting to all intents and purposes of quarts and orthoclase only or of a felspar and a ferromagnesian mineral only. These can be expressed by very simple diagrams. A system of three components really requires a solid model but this can be represented on paper by a contoured map of the model. Beyond three components representation even by models is difficult. The subject cannot be pursued here but the student will find some simple examples treated quantitatively in the book cited in the footnote.[1] Many such diagrams have been worked out in elaborate detail for industrial purposes, such as the manufacture of refractories and Portland cement and in blast-furnace practice.

Porphyritic Structure.—In some crystalline rocks the texture is fairly uniform, so that it is apparent that crystallisation has been a continuous process carried on under uniform conditions without noticeable interruption. But in other cases the rock shows comparatively large and well-formed crystals of one or more minerals embedded in a *groundmass* or base of much finer texture, or even glassy. This constitutes what is known as the *porphyritic* structure. The explanation usually given is that this is due to crystallisation or solidification in two stages, under different conditions. The simplest case is where the magma at the time of intrusion or extrusion contained ready-formed crystals

[1] Rastall, *Physico-Chemical Geology*. London: Arnold, 1927, Chapter VI.

enclosed in the molten liquid. The liquid part then solidified quickly as a finely crystalline or glassy mass, enclosing the porphyritic crystals or phenocrysts. This explanation is supported by the fact that these phenocrysts have often undergone a certain amount of corrosion, or *resorption*, having their angles rounded off, and showing signs of a partial re-solution. This is probably due to change of conditions, and especially to relief of pressure, during the transit of the magma to its present position. Porphyritic structure is specially characteristic of lavas and the smaller intrusive masses, and is more rare in large and deep-seated intrusions. Porphyritic structure might also be produced without any change of conditions at all in the crystallization of a completely liquid magma if the phenocrysts represent the excess of one or more components over the eutectic ratio for the whole, the ground-mass being the eutectic mixture.

Rock-forming Minerals.—The number of minerals in the igneous rocks is very great, but many of these are rare and of little importance, either theoretical or practical. The important rock-forming minerals can, in practice, be referred to comparatively few groups, and if we disregard many of the names needlessly conferred by systematic mineralogists and petrographers on slight variations, the number can be reduced to quite reasonable limits. Most of them are not pure compounds, having a fixed chemical composition, but are mixed crystals, composed of two or more isomorphous substances. When looked at in this way, the mineral groups can be, to a certain extent, correlated with the isomorphous groups of chemical constituents previously enumerated (see p. 252). The common rock-forming minerals may be classified on this basis as follows:

I. Accessory minerals.
II. Ferromagnesian minerals.
III. Felspars and felspathoids.
IV. Quartz.

GROUP I. THE ACCESSORY MINERALS.—This group includes a considerable number of minerals of very different composition and character, widely distributed in small quantities. In certain exceptional cases, however, they may form an important part of the rock. Most of the rarer constituents of the magma are found to crystallise in the minerals of this group. It is impossible here to do more than mention a few of the commonest, such as apatite, sphene, zircon, ilmenite, pyrite, and the various members of the spinel group, especially magnetite and chromite.

GROUP II. THE FERROMAGNESIAN MINERALS.—Under this heading are conveniently included a considerable number of silicates of various metals, especially magnesium, iron, and calcium; in some of the subdivisions the alkali metals are important constituents, while other metals, such as chromium, manganese, barium, etc., frequently occur in

small quantities. These minerals form the chief dark-coloured constituents of the rocks. The varieties recognised are rather numerous, but they may be subdivided and summarised as follows:

(*a*) The micas.
(*b*) The amphiboles.
(*c*) The pyroxenes.
(*d*) The olivine group.

All these minerals are silicates, and for the most part silicates of magnesium, iron, and calcium: in some cases, when derived from highly alkaline magmas, the alkali metals, especially soda, enter into their composition. Many of the mica group contain alkalis as normal constituents. The constitution of most of these minerals is fairly complex, but they can all be referred to one or other of the two chief acids of silica, orthosilicic and metasilicic acids. The micas, olivine and garnet are orthosilicates, while the amphiboles and pyroxenes are metasilicates.

Each of these groups contains numerous varieties, regarded by mineralogists as species, thus—

Micas—muscovite, biotite, phlogopite.
Pyroxenes—augite, enstatite, hypersthene, aegirine.
Amphiboles—tremolite, hornblende, arfvedsonite, riebeckite.

GROUP III. THE FELSPARS AND FELSPATHOIDS.—This group includes two natural subdivisions: (1) the true felspars and (2) the felspathoids.

The felspars are essentially aluminosilicates of the alkali metals or lime, or mixtures of these. They divide themselves more or less naturally into two groups, the potash felspars, including orthoclase and microcline, both of which have the composition $KAlSi_3O_8$, and the plagioclase group, which are most conveniently regarded as isomorphous mixtures of the two end products $NaAlSi_3O_8$ (albite) and $CaAl_2Si_2O_8$ (anorthite). The members of this isomorphous group are conveniently designated *soda-lime* or *lime-soda* felspars, according to whether the soda or the lime molecule is dominant. There also occurs very commonly a minute intergrowth of orthoclase (or microcline) and albite known as perthite. The discrimination of all these varieties depends on delicate optical tests described in the special treatises before cited. The felspars are the most widely distributed and the most important of the minerals of the igneous rocks.

The felspathoids, nepheline, sodalite and leucite, are silicates rather similar to the felspars, but with less silica: they crystallise from magmas with an unusually high ratio of alkalis to silica.

GROUP IV. QUARTZ.—When the magma contains more silica than is required to combine with the basic oxides to form silicates, the excess of silica crystallises in the form of quartz.

Order of Crystallisation.—The usual order of crystallisation of minerals

from a magma was established by empirical observation before it was realised that magmas are solutions (melts) and must obey the laws of solution. There is no real distinction between a fused silicate melt and a watery solution, although in the popular mind the idea of a solution is always associated with water. It was found that the order of crystallisation was of increasing silicate percentage, or as Rosenbusch preferred to state it, a *law of decreasing basicity*. We find therefore that the accessory minerals (non-silicates) crystallise first, then the ferromagnesian minerals with low silica, then the felspars (and felspathoids, if any), then quartz. But in certain basic low-silica rocks felspars crystallise before the ferromagnesian minerals. These relations are not arbitrary: they depend on well-known laws of physical chemistry, and are an expression of the fact that the order of crystallisation from a complex melt is a function of the composition and depends on the solubility of the components in the particular solution. The freezing-point of a component in a mixed melt is not the same as the freezing-point of the same component in a pure state, since every component of a mixed melt lowers the freezing point of all the other components, water and other volatiles having a specially powerful effect. Hence a deep-seated magma, rich in volatiles, may remain liquid down to a much lower temperature than a surface lava of the same original composition from which the volatiles have escaped. Rosenbusch's law is really a statement of the fact that natural magmas are all rich in silica and do not actually vary very widely in composition: true igneous rocks with less than 40 or more than 75 per cent. of silica occur only in small quantity in the world. The number of pages of a text book of petrology occupied by a particular group of rocks is no criterion of the amount of such rocks actually existing. At least 90 per cent. of all known rocks are either granite or basalt.

The Classification of the Igneous Rocks.—The classification of the igneous rocks here adopted is twofold, based partly on physical characters and partly on chemical composition. The physical characters are controlled by the conditions, and in particular by the rate of cooling; pressure may also have some influence here, but this is a somewhat obscure part of the subject. The most obvious division from this point of view is into *intrusive* and *extrusive* rocks. The intrusive rocks, however, show a very wide range of structure, so that it is found convenient to subdivide them again into two groups. The *plutonic* rocks are those large and deep-seated masses which have cooled slowly; they consist therefore entirely of crystals of various minerals (holocrystalline rocks). They are also usually coarse in texture, and typically non-porphyritic. In contradistinction to these are the *hypabyssal* rocks, the minor intrusions, which occur either as small independent masses, dykes or sills, or else as small offshoots or apophyses from plutonic intrusions. They have in consequence cooled somewhat quickly, since

the loss of heat from small masses is rapid, owing to the large amount of surface in contact with cold rock in proportion to the total volume. These rocks commonly possess a character showing an approach to that of the extrusive rocks; they frequently contain more or less glass, and are often porphyritic. Frequently, however, they only differ from the plutonic rocks in their finer texture.

It must be remembered, however, that the distinction between plutonic and hypabyssal rocks is purely arbitrary and among intrusions every gradation can be found from the coarsest granite, forming a mass many miles across, through all degrees of crystalline texture down to dykes and sills of pure glass, petrographically indistinguishable from the glassy lavas.

The extrusive or *volcanic* rocks, on the other hand, are poured out on the surface as lava flows, and they possess the characters proper to their mode of origin. They generally contain more or less glass, and some are wholly glassy. The surfaces of lava-flows always show more or less of a slaggy or cindery appearance, and the lava itself is freqeuntly spongy in texture from the occurrence of vast numbers of gas or steam bubbles. These criteria are usually sufficient to distinguish between an intrusive and an extrusive rock. Besides this, however, there is also the evidence provided by the alteration produced by the heated magma on its surroundings. A lava-flow can obviously alter only the underlying rock; and sediments subsequently laid down cannot be affected by it. An intrusive sheet injected along the bedding planes of an already existing rock must, however, alter the rock above as well as below, and this affords a certain test for discriminating the two classes.

For the reasons briefly sketched above it is found convenient to adopt a threefold classification of the igneous rocks, into the plutonic, hypabyssal and volcanic groups. Each of these groups may comprise rocks derived from magmas of any composition, so that under each heading a large number of rock-types is included. In fact, each group may and does comprise the whole range of variation of composition possible in an igneous rock. Hence it is necessary to adopt some other factor as a basis for the subdivision of these groups. The factor most usually adopted is chemical composition, which, as already explained, controls the minerals formed from the magma; hence in practice the basis of classification is twofold, partly chemical and partly physical.

Since the most important constituent of igneous rocks is silica, its percentage naturally plays an important part in classification. According to the amount of silica present it has become customary to divide rocks into four groups, called *acid*, *intermediate*, *basic* and *ultrabasic* respectively. The acid group alone contains free quartz; the intermediate rocks are specially characterised by felspars with dominant alkalis; the basic group by felspars with lime dominating alkalis;

while the ultra-basic group contains no felspar, or else a pure lime-felspar, without alkalis. However, if we attempt to classify by this means alone, we find that the intermediate and basic groups must contain rock types of very different character, which are clearly distinguishable into two sets characterised by special chemical and mineralogical peculiarities—the alkaline and subalkaline series before referred to (see p. 253). For this reason it becomes necessary to divide the intermediate and basic rocks into two groups, alkaline and subalkaline. The relations of the groups thus obtained may be shown diagrammatically, as follows:

	Alkaline intermediate	—	Alkaline basic	
Acid				Ultrabasic
	Subalkaline intermediate	—	Subalkaline basic	

Each of these divisions of course includes plutonic, hypabyssal and volcanic representatives, and separate names are applied to each: hence we finally obtain eighteen major rock-classes as set forth in a corresponding arrangement in the table.

	Trachyte	Alkali-basalt	
	Porphyry	Alkali-dolerite	
	Syenite	Alkali-gabbro	
Rhyolite			Ultrabasic lavas
Quartz-porphyry			Peridotite-porphyry
Granite			Peridotite
	Andesite	Basalt	
	Porphyrite	Dolerite	
	Diorite	Gabbro	

Unfortunately the nomenclature of the igneous rocks is in a very confused state, many names having been used vaguely and in two or more senses. The names here chosen are for the most part those employed in Harker's *Petrology for Students*, the chief difference being in the alkaline basic rocks, for which no generally accepted group-names exist, although many varieties have been described under special names, usually derived from the locality where the rock was first discovered. It may be well to mention here, for want of a more suitable opportunity, that alkaline rocks, though showing much variation, are really of very minor importance compared with the calc-alkaline suite. Taking the whole world, they perhaps do not amount to more than one per cent. of the total bulk of the igneous rocks of all classes.

Since transitional forms exist between all these classes, there naturally are rocks not definitely either alkaline or calc-alkaline but intermediate between them. In some classifications, therefore, two more groups are introduced, one between the syenites and the diorites, and a corresponding basic member. These are called the monzonite suite (from Monzoni in the Tyrol, where they were first recognized), but this only makes the subject still more complicated, and they are therefore

omitted here. Any kind of a pigeon-hole system applied to rocks must necessarily be arbitrary as there are in reality no partitions. Rock names must not be regarded in the same precise light as nomenclature of genera and species in biology; since they are applied to arbitrarily defined groups in continuous series, or more correctly still to arbitrarily defined blocks in a continuous three-dimensional model, in which two of the axial co-ordinates are chemical (or mineralogical) and the third physical (mode of occurrence, which controls rate of cooling and grain-size).

Mineralogical Composition of the Plutonic Rocks.—We may now proceed to consider the mineralogical composition of a typical member of each family. For this purpose the plutonic rocks are selected, since they are always wholly crystalline and there are no complications from the presence of glass. The facts are most easily set out in the table on page 263, where of necessity the columns have to be arranged side by side, instead of in a double series as on page 261. Here again all transitional forms are ignored for the sake of simplicity, although such types as quartz-syenite, intermediate between granite and syenite, and quartz-diorite, between granite and diorite, are very common, especially the last-named.

The arrangement of the table perhaps requires some explanation. The minerals are divided into five groups: quartz, felspar, ferromagnesian minerals, felspathoids, and iron ores. In each group a number of names are given, but it is not meant to imply that all of these occur in any given rock. One, two or more of them may be present, or possibly all in exceptional cases. The ferromagnesian minerals present are largely used to characterise minor varieties of each group. Hence we arrive at such designations as muscovite-granite, hornblende-syenite, olivine-gabbro, etc. The felspathoids are not essential to the definition of the groups in which they occur, but they are characteristic of important subdivisions of these groups.

An examination of this table shows clearly that the distinction into alkaline and subalkaline series makes itself manifest in mineralogical as well as in chemical composition. This can be illustrated by tabulating some of the characteristics of each group in parallel columns, thus—

Alkali Group.	Subalkali Group.
Alkali felspars occur in both acid and basic members.	Alkali felspars confined to acid members.
Felspathoids common.	Felspathoids absent.
Ferromagnesian minerals often soda-bearing.	Ferromagnesian minerals without alkalis.
Arfvedsonite, riebeckite and aegirine characteristic.	Rhombic pyroxenes characteristic.

For mineral names here used for the first time in this book, reference should be made to the text-book of mineralogy quoted in the footnote on page 11.

Granite	Syenite.	Diorite.	Alkali-gabbro.	Gabbro	Ultrabasic.
Quartz					
Orthoclase Microcline Perthite Albite	Orthoclase Microcline Perthite Albite	Plagioclase (soda-lime)	Orthoclase	Plagioclase (lime-soda)	(Anorthite)
Muscovite Biotite Hornblende Augite Hypersthene	Biotite Hornblende Arfvedsonite Riebeckite Augite Aegirine	Biotite Hornblende Augite Hypersthene	Augite Aegirine Olivine	Augite Olivine Hypersthene	Olivine Augite Hypersthene Hornblende
	Nepheline Leucite Sodalite		Nepheline Leucite		
				Iron-ores	Iron-ores Spinels

Differentiation in Igneous Magmas.—It has already been pointed out that the igneous rocks of a region often show resemblances among themselves so marked as to suggest a relationship by descent from a common origin. These resemblances are ultimately chemical, since the minerals actually formed are determined by the original composition of the melt. This subject has already been discussed to some extent in dealing with the differences between the calc-alkaline and alkaline suites, when it was shown that unusually high proportions of potash or soda or both lead to the formation of felspathoid minerals, such as nepheline, analcime or leucite, together with dominance of highly alkaline

felspar. This is the broadest distinction of all, and leads to the primary divisions here employed and to the conception of alkaline and calc-alkaline petrographical provinces on the largest scale (see p. 253). But when we come to consider smaller units, igneous complexes, the same kind of thing is often noticed; chemical and mineralogical similarities running through all the members of one complex. Moreover, it can often be shown that these members have been intruded in some regular order, usually increasing silica content, with concurrent regular variations in the percentages of the other constituents. All of this suggests derivation of these partial magmas by some physical process from one initial magma. The name usually applied to this hypothetical process is *differentiation*. Although it is beyond doubt that something of the sort has taken place in innumerable instances, there is much difference of opinion as to what process or processes brought it about. One point of high importance is that we do not know to what extent large intrusions make room for themselves by melting and incorporating the rocks originally occupying the space. It is argued that magmas are not usually hot enough to fuse any considerable quantity of cold rock. This is a purely thermodynamic argument, taking into account the question of latent heat. From a study of the marginal phenomena of large intrusions it is quite clear that some melting does take place, and some petrologists think that the emplacement of intrusions is largely due to such a process, which is called overhead stoping, by analogy with the mining term, but it seems extremely doubtful whether a magma could melt down its own bulk of cold rock.

At any rate it is clear that in many instances marginal modifications of large intrusions are due to incorporation of the surrounding rocks. Frequently blocks can be seen as it were floating in the intrusion and more and more altered away from the margin, even to complete fusion and recrystallisation. Such are called *xenoliths*. Their nature and consequent effect on the igneous rock can obviously vary without limit.

Another method suggested for the formation of marginal basic modifications without assimilation is a form of diffusion in the magma during cooling. Minerals of highest freezing-point separate early near the cooler walls, and molecules of the same composition are supposed to diffuse towards the margins in an endeavour to restore equilibrium. Thus early-formed basic minerals are concentrated near the walls, leaving the centre more acid. In this way it is supposed that basic margins could be formed at the sides or even at the top of an intrusion, against gravity.

It is often found in large flat-lying intrusions, such as the Palisades of New York, that the composition varies in a more or less regular manner from bottom to top, being more basic below and more acid above. The basic ferromagnesian minerals and the iron ores are

heavier than the acid felspars and quartz, and also have higher freezing-points, so that they should naturally separate first and settle down in the liquid magma. It is therefore believed that crystal sinking is an important factor in differentiation after intrusion. The same idea has also been extended to the formation of stratified partly crystallised magmas in depth, successive intrusions being attributed to the drawing off of drafts on this deep-seated source. It is even possible that such stratified magmas may have solidified in depth, and been afterwards partly melted again and brought up to higher levels as intrusions. If the melting went on from below upwards, this would account for the common sequence from basic to acid in the order of intrusion in plutonic complexes. Another cause that has been suggested for differentiation is the squeezing by earth-movements of a partly consolidated magma, which must at some stage have a structure like a sponge full of water. The residue thus squeezed out will contain the constituents of lowest freezing-point under the given conditions, usually the most siliceous minerals, with water and dissolved gases (see section on pneumatolysis).

It is by no means uncommon to find masses of sulphides and other ore-minerals at the base of large basic intrusions, perhaps the best-known example being the nickel ores of Sudbury, Ontario; moreover, as will appear in a later chapter, the association of sulphide ore deposits and igneous rocks is very close. Since it is known that the mutual solubility of fused silicates and sulphides is very small, their relations are explained on theoretical grounds as due to the separation of immiscible liquid phases, just as in artificial copper matte smelting, the heavier sulphide phase naturally settling down at the bottom as in a furnace.

Sequence of Rock-types.—Many attempts have been made to establish a definite order of succession of the different rock-types, from acid to basic or the reverse. Different authorities have arrived at very diverse conclusions, but this may perhaps be explained by the fact that some studied extrusive rocks and others intrusive. It appears probable that the sequence is different in these cases, and that even in the larger and smaller intrusive series it is not the same. It must be confessed that the evidence is very conflicting and far from conclusive, but the general conclusions now arrived at may be summarised somewhat as follows. In the volcanic rocks an eruptive series usually seems to begin with an intermediate type, trachyte or andesite, and at later stages the lavas may vary either towards the acid or the basic end of the series, with frequently a relapse to the other extreme as a final stage. A common succession is andesite, rhyolite, basalt. In other localities the acid phase comes last, and the only general conclusion which we are at present able to draw is that frequently the succession seems to be one of increasing divergence from a mean

type. In the case of the plutonic rocks, however, rather more definite results have been obtained. In the most satisfactory cases the succession seems to be almost invariably from basic to acid, whereas in the hypabyssal rocks an inverse succession has in some cases been established. This double sequence is very clearly seen in the case of the Tertiary igneous rocks of Skye, as described by Dr. Harker. Here the full succession in the three phases is as follows:

Volcanic phase.	1. Small intermediate eruptions of trachyte and agglomerate. 2. Plateau basalts.
Plutonic phase.	3. Ultrabasic laccoliths (picrites, peridotites, etc.). 4. Gabbro laccoliths of the Cuillin Hills. 5. Granite and granophyre laccoliths of the Red Hills.
Phase of small intrusions.	6. Acid dykes and sills, quartz-porphyries and pitchstones. 7. Great group of dolerite sills. 8. Ultrabasic sills and dykes.

So far as the plutonic rocks are concerned, the Permian intrusions of the Oslo district obey the same general law, each successive laccolith being more acid than the preceding one, so that there is a series from olivine-gabbro, through nepheline-syenite and syenites of increasing quartz-content, to granite. In these cases it is supposed that the different partial magmas have split off under deep-seated conditions from a primitive magma having special characteristics, which therefore are found in the whole of the rocks of that series and district. This gives rise to igneous complexes when on a small scale, and to petrographical provinces when on a large scale, and is called by Brögger *deep-magmatic differentiation.*

Complementary Series.—A large intrusion is often accompanied by numerous apophyses, usually in the form of radial dykes. These frequently show a clear division into two types, acid and basic, without intermediate forms. For example, the dykes round the Shap granite include quartz-porphyry and a very basic type consisting mainly of ferromagnesian minerals (lamprophyre), while round the Cheviot granite we find quartz-porphyries and mica-porphyrites. Again in the Oslo district the dykes belonging to the most basic laccolith (an alkaline olivine-gabbro called essexite) include bostonite, which is an almost pure alkali-felspar rock, and therefore acid, and camptonite, a very basic hornblende-lamprophyre. Analysis shows that these two rocks mixed in a certain proportion would correspond almost exactly to the composition of essexite, and it is believed that they are differentiation

products of the essexite magma, somehow separated from it before solidification, though the nature of the process is not clear. The theory of complementary differentiation explains why certain groups of dyke-rocks, especially the lamprophyres, do not fit well into the general scheme of classification.

Pneumatolysis.—Besides the elements of the ordinary minerals of the igneous rocks, magmas, especially those of acid nature, often contain in small quantities elements of low atomic weight, as well as much water. During freezing these naturally concentrate in the last residue, forming a gas phase. This, besides being under high pressure is chemically very active, owing to the presence of fluorine, boron, sulphur, phosphorus, etc., and sets up changes not only in the minerals already formed, but also in the surrounding rocks, giving rise to such minerals as tourmaline, topaz, fluor-spar, lithia-mica, beryl, apatite, etc. The processes are often accompanied by the formation of important ore deposits containing tin and tungsten as oxides, and many other metals as sulphides. Another important product of pneumatolysis is china clay, formed by the decomposition of felspar. All of these effects are well seen in Cornwall. Other instances are mentioned in the chapter on ore-deposits.

The detailed study of pneumatolysis, even in its simpler forms, involves a considerable knowledge of mineralogy. Reference should be made to a textbook of petrology.

Pegmatites.—Closely allied to pneumatolysis is the origin of the coarse-textured veins and masses of crystalline minerals collectively known as pegmatites. These are dykes, veins or irregular masses, usually either traversing igneous rocks of more normal texture, or occurring as offshoots or fringes of such masses. They are often of very coarse texture so that individual crystals may be measured by inches or even by feet. They also show very frequently a strong tendency to a *graphic* intergrowth of two minerals, usually quartz and felspar. They possess as a rule the same general mineralogical composition as the normal igneous rock with which they are associated, but there is usually a somewhat higher proportion of acid minerals, and they are frequently characterised by the occurrence of special minerals, often including compounds of the rarer elements.

Metamorphism.—Rocks do not always remain indefinitely in their original condition, but often undergo various modifications. The reference here is not to the processes of weathering and denudation under the influence of surface agencies, within the range of ordinary temperature and pressure, but to changes brought about deep down in the earth at high temperatures or high pressures, or both. The whole subject is extremely complicated and only the merest outline can be attempted here.

The way in which deep burial of sediments can be brought about is

apparent from what has been said in the chapter on earth-movements. Even simple geosynclinal deposition of sediment to a very great thickness will necessarily cause an increase of temperature in the lower layers, from the blanketing effect. Moreover, intrusions of igneous magma often take place under no very thick cover, with considerable attendant metamorphism, though the effect of surface flows is as a rule trifling. The most notable and typical effects of high temperature are seen round large plutonic intrusions, especially granites.

In the first place it must be made clear that the effects are very different in the two great classes of rocks, the igneous and the sedimentary. The ultimate reason for this is really a question of stability under the given conditions. The minerals of the igneous rocks are such as are stable under high temperatures and high pressures (except in certain surface lavas), while those of the sediments are stable at normal temperatures and atmospheric pressure. Therefore the effects of rise of temperature and pressure are more marked in the sedimentary than in the igneous group.

It is doubtful whether rocks are ever subjected to an important rise of temperature without some increase of pressure, and similarly a considerable rise of pressure would certainly generate heat. Nevertheless, it is possible to discriminate in a general way the effects of the two causes; in other words, metamorphism can be divided into two categories; *thermal* and *dynamic*. Also it is broadly true to say that in the first of these the changes produced are mainly mineralogical and in the second largely structural, though new minerals are also formed. In both cases the rocks commonly become more crystalline, and often coarser in texture than before. Only in a few cases of extremes of pressure is all structure more or less completely rolled out. There is an important difference between the effects of pressure equal in all directions (hydrostatic pressure) and differential pressure involving a shear or stress (see p. 271).

Thermal Metamorphism of Sediments.—The simplest case is brought about by the intrusion of a mass of igneous rock into sedimentary strata. In determining the effect produced the most important factor is obviously the maximum temperature attained, and as a corollary to this, the rate of cooling: the time factor is of great importance. An intrusion of molten magma, such as granite, must necessarily be at a very high temperature, often obviously sufficiently high to melt down and incorporate more or less of the sediment, as before noted. It is very common to find xenoliths of the sediment suspended in the intrusion and showing varying degrees of alteration, up to complete fusion.

But at present we are mainly concerned with the effects of rise of temperature on the unmelted rock, outside the limits of the intrusion. Here, besides the physical factors just noted, maximum temperature and rate of cooling, the most important thing is obviously the chemical

and mineralogical composition of the sediment. This is in reality the determining condition, so far as the mineral composition of the final product is concerned, but in some instances there has clearly been transfer of material, as liquid or gas, from the intrusion to the sediment.

Since there must necessarily be a gradual decrease of the maximum temperature attained away from the margin of the intrusion, with a consequent lessening of the degree of alteration, and since some sedimentary rocks are of complicated composition, such that their constituents may combine to form different minerals at different temperatures, it is often possible to map out zones characterised by special minerals around an intrusion. (When considered in three dimensions, they are of course concentric shells, not flat zones.) The whole area within which alteration can be traced is called a *metamorphic aureole.* The width of such aureoles varies from a few feet to many hundreds of yards, according to the temperature and the susceptibility of the rocks to alteration.

Sediments vary almost indefinitely in composition and it is only possible here to select a few types of the commonest occurrence, such as sandstone, arkose, clay and shale, limestone and so on. For a fuller treatment reference must be made to a special treatise.[1]

The simplest case is a sandstone with quartz cement: since this consists entirely of silica no chemical reactions are possible and the rock can only recrystallize as a mosaic of quartz; a quartzite, the distinction between the original grains and cement disappearing. If the cement is calcareous, lime silicates may be formed. Micaceous sandstones and flags form micaceous quartzites or quartz-mica-schists according to whether lamination was or was not originally well developed. White mica seems to be stable under nearly all conditions.

Many highly felspathic sandstones (arkose) have a composition much like that of granite, though usually with more quartz, and such a rock when metamorphosed may be very like a granite (granulite). If originally well bedded it may look like a gneiss (see p. 29).

The chief constituents of the clay-rocks are silica and alumina with more or less lime, magnesia, iron and alkalis; hence when metamorphosed various aluminous silicates are formed, either simple or complex, according to the proportions of the other constituents present: at very high temperatures felspars, garnet, and micas may be formed from impure clay-rocks. With a low grade of alteration a common result is the appearance of spots, which usually seem to be imperfect crystals of silicates. Since the grain of metamorphosed clay-rocks is usually rather fine, they are often described collectively by the German term *Hornfels*, though in many cases the appearance is by no means horn-like, but distinctly granular and crystalline.

[1] By far the best book on the whole subject is, Harker, *Metamorphism.* London, 1932.

The thermal metamorphism of limestones, pure and impure, is an interesting but complicated subject: it can only be dealt with here very briefly in the most general terms. The carbonate minerals are readily recrystallized by heat, where dissociation is prevented by deep burial, and the result is marble, either calcitic or dolomitic. Aragonite always recrystallizes as calcite. If the limestone or dolomite-rock is impure, an endless variety of minerals may be formed, most commonly silicates of calcium or magnesium or both. This gives rise to many of the most beautiful ornamental marbles. If the pressure is high, varieties of garnet are commonly formed.

As for the actual processes taking place during thermal metamorphism the ordinary rules of chemical reactions apply, and the simpler cases can be represented by equations. Many of these reactions are no doubt theoretically reversible, but in practice the minerals formed at high temperatures usually remain as such, though many of them must really be in a state of unstable equilibrium. One of the most important points is that silicates always form, if possible, being the stable form of the components at high temperatures. Nearly all rocks, and especially sediments, always contain a good deal of water, and given sufficient time the final result is much the same as if the sediment had been reduced to what may be called aqueous fusion: i.e. really rather like a molten magma. It follows from this that the result is not always the same as what would be expected from comparison with *dry* melts in the laboratory.

Igneous magmas often contain, as stated on page 267, a considerable proportion of the so-called volatile constituents, boron, fluorine, sulphur, phosphorus, and in this group water must also be included. The result is the addition of these constituents to the sediment and the formation of a peculiar class of minerals, some of them the same as in pneumatolysis of igneous rocks. Such a process of addition of material is called metasomatism; this term is often extended to other processes of rock-alteration by addition at ordinary temperatures. Some of the best-known instances of metasomatic metamorphism are the development of tourmaline in sediments around granites and of fluorspar in limestones. Sometimes also important sulphide bodies are formed by replacement of limestones. Further reference will be made to this subject in the chapter on ore-deposits.

Dynamic Metamorphism.—The movements which have affected the lithosphere have in most cases left clear traces of their action, and the sum-total of the phenomena thus occurring are comprised under the general heading of dynamic metamorphism. It is not always possible to discriminate clearly between the effects directly due to pressure and those due to the heat generated by friction, and there is evidence that the effects of thermal metamorphism are in some cases complicated by mechanical stresses directly due to the intrusive mass. Some of

the mechanical effects of pressure acting on rocks have already been considered in the Introduction (folding, faulting, cleavage, foliation, etc.), and these do not here require description, so far as they relate to structures produced on a large scale. We are here concerned rather with the minuter structural and mineralogical changes resulting from pressure: that is to say, with the petrography of the metamorphosed rocks.

The changes produced by stresses of compression and shearing may be divided into two heads: *physical* and *mineralogical* or *chemical*. The most conspicuous of the physical changes, at any rate to the naked eye, are cleavage, foliation and schistosity. These are, in part, simple rearrangements of the constituent particles of the rocks, adjustments to pressure; but they also in most cases involve a good deal of recrystallisation of existing minerals and formation of new minerals.

It is evident that deep burial under a thick cover must lead to increase of pressure and it is easy to calculate that at a depth of some tens of thousands of feet rocks must be under a pressure of an incredible number of tons per square inch, but this pressure is equal in all directions, i.e. hydrostatic, and it is not this kind that produces the typical effects. It is merely compression and its chief effect is to raise the temperatures at which chemical reactions and especially fusion can take place. But it has been shown that differential pressure involving a shear, has exactly the opposite effect and in a much higher degree, thus facilitating mineralogical reconstruction. Furthermore, out of any number of possible combinations of a given set of components into minerals, the stable one at high pressures is necessarily that having the least volume, or in other words the highest density. Therefore it follows that the characteristic minerals of dynamic metamorphism are those having a high density such as garnet, or those adapted to arrange themselves in ways consistent with unilateral pressure, namely platy, needle-like or fibrous forms, such as micas, chlorites and some varieties of amphibole and certain aluminium silicates. These are called stress-minerals.

Crush Breccias and Crush Conglomerates.—Folding and faulting in resistant rocks are often accompanied by a considerable amount of fracture on a comparatively small scale, by which the rocks are broken up into fragments, which may subsequently become cemented together again in the usual manner by deposition of cement, etc., thus simulating ordinary clastic structures, such as breccias and conglomerates. They can, however, as a rule, be distinguished easily from true fragmentary rocks by the fact that the fragments are all of one kind, whereas clastic breccias and conglomerates are almost always *polygenetic*, being composed of fragments of different kinds of rock. Sometimes the broken masses remain angular, forming a crush breccia: this is particularly common along fault-planes, where the fissure is frequently filled by a

mass of angular fragments of the country rock, the so-called fault-breccia. In other cases, however, there has been so much rolling and crushing that angles become rounded off, and the whole simulates very closely the appearance of a bed of water-worn pebbles, a true sedimentary conglomerate.

Lenticular or 'Eyed' Structure.—When a mass of rock containing elements of varying hardness, or crystals of conspicuously large size, is subjected to crushing stresses, the softer or smaller fragments are frequently rearranged in streaks with approximately parallel structure, with a strong tendency to flow round the larger or more resistant masses: these in their turn are often more or less rounded off or flattened, so that the whole assumes a sort of lenticular appearance, which may be called *eyed structure* ('Augen Struktur'). This is very apparent in many crushed porphyritic rocks, forming *eyed gneiss* or *augen gneiss*. This type of structure passes by every gradation into ordinary foliation and schistosity.

Structural Changes in Minerals.—On a smaller scale than the phenomena just described are the structural changes resulting from the crushing of crystals. These changes are mostly to be observed in microscopic sections, and are connected with strains of compression and recrystallisation, which frequently involve addition of material to existing crystals, along lines of least resistance. When examined in polarised light, the crystals of crushed rocks frequently show an alteration of their optical properties: for example, the extinction of doubly refracting crystals loses its sharpness and becomes uncertain, waves of extinction passing over the crystal as it is rotated. Again, crystals of minerals, such as garnet, normally singly refracting, frequently show double refraction. Also secondary twinning may be produced by strain, and original twin lamellae, cleavages and other linear parallel structures may become bent and distorted. In a further stage of deformation the crystals are cracked or actually broken. Such broken crystals frequently undergo more or less complete recrystallisation, so that the place of one large original crystal is occupied by a mosaic of smaller crystals of the same substance. In some cases of intense crushing, as for example in the neighbourhood of great thrust-planes, the shearing and grinding action has been so strong that an original coarsely crystalline rock is ground down to a paste of exceedingly fine texture, known as *mylonite*. This name was first applied by Lapworth to the crushed rocks affected by the movement of the great thrust-planes of the North-west Highlands. When the crushing has been less intense a structure known as granulitic is produced and the resulting rock is a *granulite*. Here the original crystals are destroyed and the material is recrystallised as an even-grained mosaic of small crystals of the same or different minerals, often with conspicuous parallel orientation and banding. This is one form of foliation, which does

not, however, imply the existence of actual planes of discontinuity, but merely a parallel arrangement of bands of minerals of varying composition and colour. This structure is very common in originally coarse-textured igneous rocks subjected to shearing strains during dynamic metamorphism.

Dynamic Metamorphism of Sediments.—The effects of dynamic metamorphism in sedimentary rocks depend to a very large extent upon the original texture of the rock. If this texture is fine the result is cleavage of a greater or less degree of perfection. Cleavage is always accompanied by a certain amount of recrystallisation and production of new minerals, and in some cases the rock appears to have been almost entirely reconstituted. Usually the characteristic mineralogical change is the formation of mica and minerals of the chlorite group. When much quartz was originally present it is, as a rule, recrystallised as a mosaic of minute grains, while other minerals, such as garnet, are often formed. When the resulting rock is highly crystalline and glossy in appearance, it is often spoken of as *phyllite*. This may be regarded as a more advanced stage of metamorphism than ordinary slate, and such rocks are as a matter of fact micro-crystalline mica-schists.

False Cleavage.—Rocks of fine texture often undergo a good deal of crumpling or folding on a minute scale, and this may give rise to a peculiar structure known as *false cleavage* (Fig. 93). When a well-bedded rock is subjected to pressure in a direction making a high angle with the original bedding, small sharp folds are produced, often unsymmetrical or overfolded, and the middle limbs of these small folds are

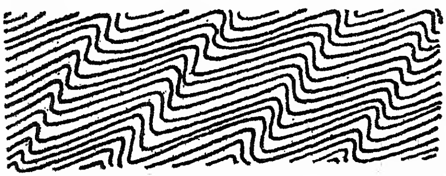


FIG. 93.—DIAGRAM TO ILLUSTRATE FALSE CLEAVAGE.

planes of special weakness along which the rock has a tendency to split. False cleavage, or *strain-slip cleavage* as it is sometimes termed, differs from true cleavage in the fact that splitting is only possible along certain planes, as can be seen from the diagram, and the rock cannot be split up into indefinitely thin layers, as in true cleavage. This structure may be observed of almost any degree of magnitude, and is very common, on an almost microscopic scale, in slates and schists.

Mineral Formation in Dynamic Metamorphism.—The dynamic metamorphism of fine-textured rocks is always, as before stated, accompanied by formation of new minerals, the character of which depends on the

composition of the original rock. Quartzose sediments, such as grit and sandstone, are converted into quartzites, which show a strong resemblance to the quartzites of thermal metamorphism, though, as would naturally be expected, optical anomalies, such as strain-shadows, are still more strongly marked. When the sandstone is impure, new minerals are formed, of much the same character as in thermal metamorphism; but in addition to this, a marked type of foliation is commonly produced, so that the altered rocks are *gneisses*, in many cases difficult to distinguish from gneisses of igneous origin. However, since the intensity of dynamic metamorphism is not everywhere the same, it is frequently possible to trace these gneisses laterally into more or less unaltered clastic sediments.

Speaking generally, we may say that, when sedimentary rocks are subjected to pressure, the changes induced are somewhat as follows. Fine-grained rocks produce slates when not much recrystallised, and phyllites or schists when highly crystalline; the term schist is somewhat vague, and is most commonly used to express rocks with a glossy or micaceous appearance, often strongly fissile, and also frequently more or less contorted, so that they do not split so evenly as slates. Coarse-grained sediments, on the other hand, produce gneisses and quartzites. It is impossible, however, to give any strict definition separating gneisses from schists. The two types pass into each other by insensible gradations. It may also be remarked here that most of the foregoing statements apply to the fragmentary rocks of volcanic origin, so far, at any rate, as structures are concerned. Many of our best roofing slates have been formed by cleavage of fine ashes, as in North Wales; while in the green slates of Cumberland the original texture was comparatively coarse, and large fragments, up to one or two inches in diameter, are still recognisable on the cleaved surfaces (e.g. the so-called 'rain-spot slate' of Borrowdale).

Dynamic Metamorphism of Igneous Rocks.—In this class of rocks as well as in sediments pressure gives rise to parallel structures, accompanied by more or less mineralogical change, and the resulting rocks are known as gneisses, schists, etc., according to their general appearance and texture. The degree of mineralogical change varies a good deal in accordance with their original composition, and the amount of alteration the minerals have previously undergone. The minerals of the acid rocks do not seem to undergo much alteration; but it is probable that in most cases there has been in reality a good deal of molecular rearrangement owing to the pressure: the minerals finally formed are of the same general character as those originally present, since the minerals of the acid rocks as a whole are those stable under conditions of high pressure and moderate temperature. Original pyroxene is often converted into amphibole, whereas on the other hand hornblende sometimes recrystallises as augite. The reason for

this variability of behaviour is not clear, but the latter change probably takes place at a higher temperature. Quartz and the felspars are more or less recrystallised, and show strain-shadows, granulitisation and other structures previously described. In the basic rocks, on the other hand, more far-reaching changes are set up, involving a good deal of molecular and chemical reconstruction. Rocks originally rich in olivine are converted into schistose aggregates of actinolite, anthophyllite and talc. Massive rocks such as dolerite and basalt undergo an interesting series of changes, of which the final result is a hornblende-schist or amphibolite. A special case, that of the Scourie dyke in Sutherland, has been exhaustively described by Teall. The first stage of alteration is the conversion of the original augite into actinolitic hornblende (uralitisation): the rock in this state may be described as an epidiorite. As a result of stronger pressure the felspar is also recrystallised, and the final result is a hornblende-schist.[1]

[1] Teall, *Quart. Journ. Geol. Soc.*, xli., 1885, p. 133.

CHAPTER XIII

ORE DEPOSITS

Definitions.—The geology of ore deposits is in reality nothing but the application of certain principles of structural geology, mineralogy, and petrology to the study of a class of substances that happen to possess commercial value as sources of the metals employed for various technical and industrial purposes. The accepted definition of an ore is that it is a mineral or rock containing one or more metals in payable quantities; such a definition can obviously include deposits formed in geologically very different ways; hence the classification and generalised treatment of this group presents special difficulties. To the practical man, the miner and the engineer, the points of importance are the metal-content of the deposit, its form and its extent. Hence the earlier attempts at classification were mostly based on form; it is only in comparatively recent times that the genetic principle has been introduced into the classification of ore deposits, with great advantage to their scientific study and to the practical application of such study to the search for and discovery of new ore-bodies of commercial value.

Primary and Secondary Ore Deposits.—Whatever scheme of classification may be adopted, it is necessary to draw a clear distinction between the two main classes of ore deposits, primary and secondary, which differ fundamentally in their origin and geological relations. The primary ore deposits are those in which the metalliferous minerals have been formed in the positions where they are now found, whereas the secondary ore deposits contain ore minerals formed elsewhere, and transported to their present position by processes of physical geology. In point of fact the distinction is analogous to that between igneous and sedimentary rocks. In the former category come most of the important ores of copper, lead, zinc, silver, antimony, bismuth, and many others, while the secondary group includes gold, tin, platinum, and a few more. Some of the important iron ores, together with a number of compounds of other metals, belong rather to the class of metamorphic and metasomatic rocks, some being directly due to the influence of igneous intrusions, others to alteration of rocks by solutions at the ordinary temperature and pressure. It must, of course, be understood that many metals belong to more than one category; for example, it is the working of the agents of denudation and transport

on *primary* ores of gold, platinum, and tin that gives rise to the secondary deposits of those metals, while ores of iron originate in almost every way that is geologically possible: igneous, sedimentary, metamorphic, and metasomatic. Hence it appears that the subject is complex and difficult to deal with in a satisfactory manner. Every classification, on whatever basis, must be more or less in the nature of a compromise.

Morphological Classification.—Among the older classifications, based solely on external form, that proposed by Von Cotta [1] is the simplest and most useful; it is as follows:—

I. Deposits of Regular Form—
   1. Beds.
   2. Veins.
II. Deposits of Irregular Form—
   1. Masses.
   2. Disseminations.

This scheme almost explains itself. The term 'beds' is to be taken as including stratified deposits, whether primary or secondary; the second group, 'veins,' includes all the varieties of dykes, lodes, and veins traversing rocks irrespective of direction, as afterwards explained. With regard to irregular masses, it is obviously impossible to generalise, but certain more or less definite types can be recognised. These are described in a later section (see p. 280). Disseminations may also obviously be of any form whatever, and usually do not possess well-defined boundaries.

Genetic Classification.—In recent times many different schemes have been proposed for a truly scientific classification of ore deposits, based on a consideration of their mode of origin. It is now generally recognised that the study of ore deposits is a branch of petrology, and that their formation can be referred to one or other of the ordinary categories of rock-formation, igneous, metamorphic, or sedimentary. Most of the secondary deposits are clearly sedimentary, while many of the primary ores are as clearly of igneous origin; there still remain, however, a number of doubtful cases that require further investigation. It was at one time generally believed that most, if not all, of the primary ores were formed by deposition from water at or near atmospheric temperature and pressure; that is to say, by the meteoric ground-water of the outer layers of the earth's crust. Further experience clearly showed, however, that some ores were formed at high temperatures and pressures by igneous processes, and the tendency has been to extend this to the great majority of cases. It is possible that this idea has been carried too far, but in a vast number of instances it is certain that the ores are of igneous origin. Besides these there are deposits commonly classed as due to contact and replacement. The contact deposits

[1] *Die Lehre von den Erzlagerstätten*, 1859.

are essentially metamorphic in origin, being due to the action of igneous intrusions, while the replacement deposits naturally come within the category of metasomatism, as before defined; many of the ore-bodies placed in this class are obviously due to transfer of metallic material from intrusions to the surrounding rocks. It is doubtful whether any hard-and-fast line can be drawn between these classes, since in most of the contact deposits there has evidently been addition of metallic elements to the surrounding rocks.

Primary Ore Deposits.—In this category are included, in the first place, all the ores known to be of direct igneous origin, and the contact and replacement bodies due to the intrusion of igneous rocks, or in some cases to the extrusion of lavas. The origin of such ores is essentially part of the process of differentiation of igneous magmas spoken of on p. 263, which is closely bound up with the phenomena known as pneumatolysis. When an igneous magma is undergoing differentiation, its constituents separate in a certain definite order, depending on their solubility in the magma and the amount of flux present. Ore minerals behave very variously in this respect, but it may be stated in general terms that they usually crystallise either very early or very late, according to whether the metal does or does not form volatile compounds; thus nickel, chromium, and platinum crystallise at an early stage, while tin, lead, and zinc belong to the very latest phases. One consequence of the latter type of behaviour is that deposits of tin and its companions tend to get mixed up with the processes known as pneumatolysis, which also belong to the latest phases of the cooling of an intrusion. Hence some authors have tried to classify primary metallic deposits into *magmatic*, *pneumatolytic*, and *hydrothermal*. This division is arbitrary, since no hard-and-fast lines can be drawn, but it is useful as a working basis. Under the heading of magmatic deposits are generally understood those compounds of the useful metals actually found as original constituents within the igneous rock, either scattered uniformly through its mass or segregated into masses in some particular part of it. Such segregation is due to some type of differentiation, either sinking of heavy crystals, diffusion to a cooling surface, or separation of immiscible liquids, as in the case of pig-iron and slag. All these causes are probably operative. Examples of such masses are afforded by some of the iron ores of Sweden and Norway and of the State of New York, the nickel-bearing sulphides of Sudbury in Canada, and the platinum of the Urals.

Vein Deposits.—More widespread than the foregoing are the ore deposits in the form of tabular masses or sheets, either vertical or inclined like dykes, and more rarely horizontal, like sills. As a matter of fact, they are very closely related to dykes and sills by origin as well as by form. They may be described as due to the infilling of fissures in the rock by material of igneous, pneumatolytic, or hydro-

thermal origin, or even laid down from solutions at normal temperatures. During the cooling of igneous intrusions there is commonly a tendency for the metallic constituents to concentrate in the last residues of the magma, so that they become associated with the material of the pegmatites and aplites that are intruded during the latest stages of

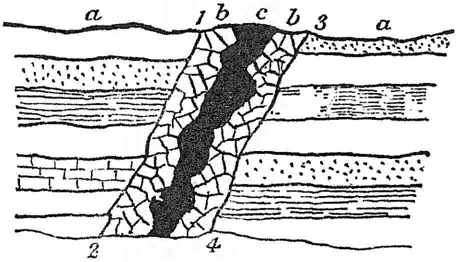


FIG. 94.—MINERAL VEIN OCCUPYING FAULT-FISSURE IN STRATIFIED ROCKS. *aa*, Sedimentary rocks, the 'country'; *bb*, Veinstone or gangue; *c*, Metallic ore; 1, 2, Hanging-wall; 3, 4, Foot-wall.

the cooling, and also with the vapours and solutions that give rise to the secondary changes in rocks and minerals known as pneumatolysis, while some of them pass out from the intrusion in the hot siliceous solutions that form quartz veins. As a matter of fact, all these stages are parts of one continuous process. Many pegmatites, consisting of, say, quartz, felspar, and mica in and near a granite, have been traced laterally without definite break into pure quartz veins, the change simply being a gradual diminution of felspar and mica when followed outwards from the granite. Metallic minerals are often present throughout such a vein, or they also may diminish in amount in the same way. Veins formed in this manner often contain an extraordinary variety of minerals, both metallic and otherwise. The valueless part is generally called the *gangue*, as opposed to the valuable part, or *ore*. In many instances it is easy to show that the filling of a vein has taken place in two or more stages (see Fig. 95), the different minerals being deposited in a definite order, and sometimes it can be proved that after filling the vein has again been opened by earth movements and another lot of minerals deposited. This may be repeated any number of times.

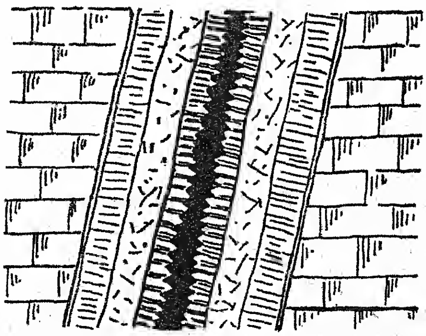


FIG. 95.—COMPOUND MINERAL VEIN.

When, as is often the case, the vein occupies a fault-fissure, it may be more or less completely filled by fault-breccia, with ore and gangue deposited in the interstices. Such brecciated lodes are common. In some parts of the world, especially in Africa, veins are often called *reefs*, from a supposed resemblance between the outcrop of a big white quartz-vein and waves breaking on submerged rocks.

When a vein is vertical its position is defined by its *strike*, just as in the case of a vertical bed. An inclined vein is now commonly defined by its strike and dip or underlie, which are measured as before described (see p. 24). Occasionally instead of dip the term *hade*, the complement of the dip, is employed, but this is rapidly going out of use. In inclined veins the bounding surface that lies uppermost is called the *hanging-wall*, that below the *foot-wall*. Since veins are often faults or lie along the contact of two rocks, these are often different. When followed by mining to a great depth the dip of a vein often changes, and may vary on either side of the vertical. The dips are commonly at high angles, not often less than 50 degrees and very often 70 degrees or more. In any given district veins often follow more or less closely certain definite directions, determined by faults or major joints in the rocks, and one set of fault-veins may intersect and shift another set, thus giving rise to complicated structural problems in determining the proper direction in which to drive to pick up the continuation of a faulted vein.

Sometimes, however, mineral deposits of this character are less definite than just described. When the mineralising solutions are traversing the rocks they may not be able to find clean-cut open channels for their passage, but may be forced to penetrate along extremely narrow cracks or through fractured zones in the rocks, such as shatter-belts. The ore minerals may then be deposited in a finely divided condition along an ill-defined belt of rock without definite walls. Such zones of deposition and ore-formation often extend outwards for some distance on either side of a narrow crack, which is called a *leader*, and the whole mineralised band may then be called a *lode*. This term, however, is not very precise, since it is often used for well-defined veins with a distinct filling; many lodes cannot be clearly distinguished from brecciated veins. Very small veins are often spoken of as stringers, and a mass of rock permeated by great numbers of small veins or stringers is called a *stockwork* (Fig. 96). Sometimes the veins in a stockwork are so numerous and close-set that the whole mass forms a payable ore, and the ore-body then differs little in practice from a dissemination.

Examples of mineral deposits of the foregoing types are innumerable in almost all parts of the world. An admirable example is afforded by the tin-copper lodes of Cornwall, which contain copper in their upper parts and tin below (Fig. 97).[1] Some of these—as, for example,

[1] Davison, *Handbook of Cornish Geology*. Penzance, 1926, with an excellent bibliography.

at Dolcoath Mine—have been worked to a depth of 3,000 feet. Here, as in so many other places, the mineralisation is accompanied by pneumatolysis, and the lodes are associated with great quantities of tourmaline, topaz, fluorspar, and other minerals rich in fluorine and boron. Tin, with tungsten, uranium, and other metals, is found in greisens, while the later lode-fillings include compounds of lead, zinc, iron, antimony, bismuth, and other metals. Gold-quartz veins are very common in many parts of the world. Some of the most important copper deposits are found as lodes and veins in connexion with igneous intrusions, as in Montana, and other parts of the United States, and in the Andes of South America. Another remarkable type of ore deposit of pneumatolytic origin is afforded by the 'pipes' of Queensland and New South Wales, which yield much tin, bismuth, tungsten, and molybdenum. These are cylindrical masses of quartz, usually from 10 to 40 feet in diameter, often con-

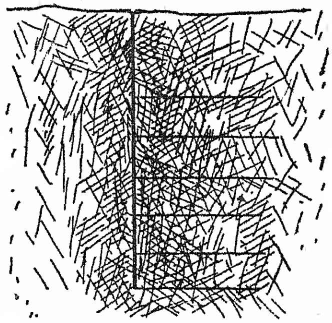


Fig. 96.—Stockwork.

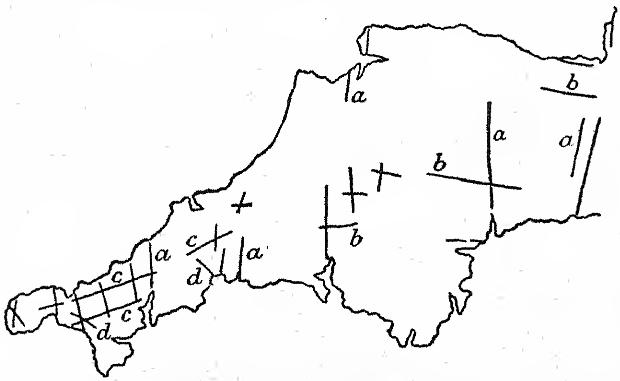


Fig. 97.—Map showing the Lodes of Devon and Cornwall. (After De la Beche.)

The set *a*, *a*, running north and south, contain lead and zinc; the sets *b*, *c*, *d*, striking in general in an east and west direction, contain the chief copper and tin ores, and are shifted by the set *a*; the shift, however, is too small to be seen on this scale.

taining also felspar and mica, with the metallic minerals arranged in zones. They seem to be formed by the passage of mineralising gases during the pneumatolytic phase of cooling, and their position appears to be determined largely by joints.

Cavity Fillings.—Closely related to the true vein deposits are certain less regular ore-bodies formed by deposition of material in pre-existing cavities in rocks (Fig. 98). This type is best illustrated by the lead-zinc ores found in the Carboniferous Limestone of many parts of Great Britain. The occurrence in this rock of open joints and cavities of all shapes, ranging up to large caverns, has already been described (see p. 73). These cavities are frequently filled by masses of galena and zinc-blende, with calcite, barytes, fluorspar, and other gangue minerals. It was at one time generally believed that these minerals were deposited by meteoric water circulating through the rocks at the ordinary temperature, in contrast to the high temperature veins before described; but there are certain difficulties in the way of this theory. In the first place, it is hard to see where the metals came from on this supposition; it is known that ground-water does not penetrate far

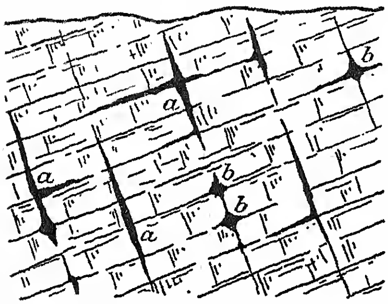


FIG. 98.—GASH VEINS, OR PIPES, AND BUNCHES IN LIMESTONE.
a, GASH veins, or pipes; *b*, Bunches.

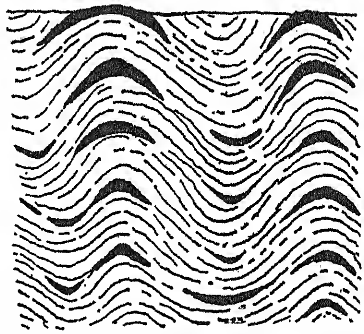


FIG. 99.—SADDLE-REEFS.

below the surface, since most very deep mines are dry. Hence it was argued that the metals must have been extracted from the surrounding rocks and concentrated in the cavities (Lateral Secretion theory). Secondly, the abundance of fluorspar certainly suggests a connexion with igneous magmas. On these grounds it is now generally believed that these deposits also are of magmatic origin, deposited by ascending thermal waters from underlying igneous rocks. In this connexion it is significant that in Cornwall the later veins contain lead and zinc, while there can be no doubt that they are due to the same primary cause as the earlier tin-copper veins.

The form of these ore-bodies in the limestones is obviously controlled by the shape of the cavities. Fillings of vertical joints form veins, the *rakes* of the Derbyshire miners; deposits along bedding planes are called *flats*, while more or less cylindrical masses formed at the intersection of two vertical joints are *pipes*. These are essentially filled-up

potholes. Various irregular masses of indeterminate form are often called *bunches* and *masses.*

When ores are deposited in highly folded rocks, they often tend to accumulate specially in the arches of anticlines and to a less extent in the troughs of synclines, owing to the existence there of places of special weakness or even open spaces (Fig. 99). The best example of this is afforded by the gold-bearing *saddle-reefs* of Bendigo in Victoria, which have yielded an immense amount of gold.

Replacement Deposits.—These occur most commonly in limestone, or dolomite, though they are sometimes found in other rocks. One of the most important examples is afforded by the great iron-ore deposits of Cumberland and the Furness district of Lancashire. Here the Carboniferous Limestone was originally covered unconformably by the very ferruginous strata of the New Red Sandstone. Water percolating through these passed down into limestone below, carrying iron in solution. When this came in contact with the calcium carbonate of

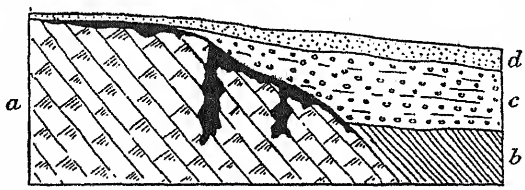


FIG. 100.—HAEMATITE REPLACING LIMESTONE IN THE CARBONIFEROUS LIMESTONE SERIES, SOUTH WALES.
a, Carboniferous limestone; *b*, Shale of the Millstone Grit; *c*, Trias; *d*, Superficial deposits.

the limestone, the iron displaced the lime of the carbonate, probably first forming ferrous carbonate, which was later oxidised to ferric oxide or haematite. These replacement bodies are usually of very irregular shape and often of great size; the Hodbarrow Mine on the Duddon estuary, which worked a single ore-body of this kind, had an annual output of about 400,000 tons of ore, averaging about 54 per cent. of metallic iron. The same effect is seen on a smaller scale in the Carboniferous Limestone of South Wales and the Forest of Dean (Fig. 100) and in some of the Devonian limestones of Devon. The highly important iron ores of Bilbao in northern Spain are due to the metasomatic replacement of a Cretaceous limestone equivalent in age to the Gault. Numerous examples of replacement and metasomatic ore-bodies have been described in many parts of the world, and some of them are of great practical importance. Where definite mineral veins traverse limestone, such bodies are often found extending outwards from the veins and thus extending their workable size. When the veins

traverse an alternation of limestone beds with more resistant strata the width of the payable portion is often much greater in the limestones.

Sedimentary Ore Deposits.—In this group are included all the rocks and unconsolidated deposits of sedimentary origin containing sufficient metal to be of value as workable ores. There are two principal categories of these—(*a*) the alluvial deposits; (*b*) the stratified iron ores. Some residual deposits are also of commercial value.

The term 'alluvium' is often interpreted by mining geologists in a rather broad sense to include besides true alluvium some of the deposits included under the heading of colluvial in the table on p. 86. Many metallic minerals are both very stable and very heavy, hence tending to survive and accumulate in superficial deposits. Such, for example, are gold, tinstone, and platinum, which are often found in quantity either on or just below the outcrop of the lode or other ore body (shoad deposits), or in transported sands and gravels formed by the ordinary geological processes in rivers, lakes, or in the sea. Owing to their high density there is often a natural sorting and concentration of such material by stream or wave action. As examples we may mention the gold gravels of Australia, California, and the Klondike; the tin gravels of Cornwall, the Malay States, and Nigeria; and the platinum gravels of the Urals. Many gem-stones also tend to occur in a similar way, as diamonds in Brazil and the Vaal and Orange Rivers, rubies and sapphires in Ceylon. In many places around the Pacific differential sorting by wave action has formed great beds of black sand, composed of magnetite and ilmenite, often with gold, and in the same way monazite sands have been formed on the coasts of Brazil and Travancore; this is the chief source of thorium for incandescent gas-mantles. In Australia and California gravels of Tertiary age, often covered by later lava-flows, have been worked extensively for gold.

Many of the most important and valuable iron ores of the world are stratified sedimentary rocks of different ages. The simplest type is the black-band and clay-band ironstone of the British Coal Measures, which appear to be in origin exactly analogous to the modern bog-iron-ore and lake-ore described on p. 174. More difficult to decide is the question of the origin of many examples of oolitic iron ore, such as those of the Jurassic system in Britain and Lorraine, the Clinton (Silurian) ores of the eastern United States and the Wabana ore (Ordovician) of Newfoundland. In many of their characters these are very like oolitic limestones, but they consist mainly of carbonate, silicate and hydrated oxides of iron. It is now generally agreed that the iron was deposited primarily in the sea, but the nature of the processes involved is unknown. For a further discussion see page 173.

Among the truly residual ore-yielding deposits, the most important

is laterite (see p. 88). In the typical laterite deposits of India three chief types can be recognised, connected by all intermediate gradations; these three types are characterised by iron, alumina, and manganese respectively. Some Indian laterites form quite good ores of iron and manganese, but it should be noted that in some tropical countries the name laterite is rather loosely applied to masses of iron ore having only a superficial resemblance to true laterite, and of different origin. The most important of the real laterite group is the highly aluminous variety, bauxite, the ore of aluminium. This occurs extensively in India, but the chief commercial supplies are obtained from deposits of earlier geological date, from North-eastern Ireland (Tertiary), from Hungary and from South-eastern France, where the original bauxite of Les Baux is found at an unconformable junction of the Jurassic and Cretaceous.

Iron Ores in Crystalline Schists.—In many areas of gneissose and schistose rocks of ancient date iron-bearing minerals are present in large quantities and in some localities they are sufficiently concentrated to form workable ores of great importance. Some of these occurrences are certainly magmatic segregations, while others in their present condition are clearly of metamorphic origin, the iron content of originally ferruginous sediments having been crystallised by heat or pressure or both as magnetite or haematite. Some of these iron-bearing rocks, formerly considered as of too low grade to be workable, can be concentrated by magnetic separation to high grade products.

Some of the highest grade iron ores in the world are found in Brazil, but owing to distance from the coast and transport difficulties they have not been much worked. They are essentially haematite-schists, the best samples approaching near to pure Fe_2O_3. Obviously they were originally sediments, possibly of lateritic type, which have undergone intense dynamic metamorphism.

The iron-bearing rocks of the Lake Superior region are of a peculiar type and indicate a more complicated history. It seems that they were originally marine sediments, largely siliceous, with only a moderate amount of iron, as carbonate and green silicate. As a result of weathering in Precambrian times the silica and other constituents were removed and the iron concentrated in favourable localities: later, the rocks underwent considerable folding and metamorphism, with crystallisation, mainly as haematite, but in some places as magnetite. As before stated the origin of marine iron carbonate and silicate rocks is still a mystery, but in this instance it has been suggested that it was in some way connected with submarine volcanic eruptions, which might also have supplied the silica from residual solutions. These rocks of the Marquette, Menominee, Penokee, Mesabi, Gogebic, Cuyuna and Vermilion 'ranges' support the largest iron-mining industry of the world. It is of some interest that at least one of them, deeply buried

under glacial drift, was discovered by magnetic survey based on the anomalous behaviour of the ordinary compass needle.

Secondary Changes in Ore Deposits.—Most of the primary ores of the magmatic, pneumatolytic, and hydrothermal groups are sulphides, only a few primary ore minerals containing oxygen. So long as these are not affected by weathering they remain unaltered, but when owing to denudation they are brought within the reach of superficial geological agencies, chemical changes begin, mainly by the action of ground-water containing carbon dioxide and oxygen. Thus the primary sulphides are oxidised to sulphates, carbonates, oxides, hydrates, and a large variety of other secondary minerals, some of which are soluble in water. These metallic solutions tend to travel downwards till they reach the level of ground-water, where reducing conditions prevail and the dissolved substances are again precipitated, either as secondary sulphides, often of complex composition, or as native metals. Thus at the bottom of the weathered zone is found a richly mineralised layer, called the *zone of secondary enrichment.* To take the simplest case, that of a lode of copper pyrites ($CuFeS_2$): near the surface this is decomposed, forming insoluble iron hydrate, which remains in place, and soluble copper compounds, which partly remain in the oxidised zone as green and blue copper carbonates, and partly pass down to be reprecipitated as various copper-bearing sulphides such as chalcocite and complex sulphides of copper and other metals; as cuprite, Cu_2O; or as the native metal. Below this rich zone the unaltered primary sulphide is found. In a similar way sulphides of lead and zinc are altered near the surface to sulphates, carbonates, and other oxidised compounds. Silver and gold are often concentrated in the zone of secondary enrichment from the very small amounts present in the primary ore; thus rich deposits, or bonanzas, may be derived from original low grade primary ores.

In a very similar way the outcrops and oxidised parts of beds of iron-ore are often much richer than the unweathered portion below. In the case of iron-ores, however, the oxidised iron compounds are mostly insoluble, and the concentration is largely due to removal of other more soluble substances, especially lime, from the weathered parts.

The Mineral Composition of Ore Deposits.—The total number of minerals which can be exploited as sources of metals is very great, and it is impossible to give here anything like a complete list of them. For this systematic works on the subject must be consulted. It may be well, however, to give a very brief résumé of the principal sources of the commoner metals without entering into any detail.

It is necessary to draw a clear distinction between the metalliferous portion of the deposit, the *ore minerals* in the narrow sense, and the worthless associates or *gangue.* Some of the gangue minerals may have a value for special purposes, though not as sources of metals. The most

common gangue minerals are quartz, calcite, dolomite, barytes, and fluorspar. Siderite (chalybite) is not uncommon in mineral veins, and may be regarded either as gangue or ore, according to whether it is utilised as an iron-ore or thrown away as worthless. This depends mainly on questions of transport and markets. Barytes is of value in the manufacture of paint and paper, and fluorspar is employed as a flux in certain metallurgical processes.

The principal metals of value, in the commercial sense, occurring in true ore deposits are as follows: gold, silver, platinum, mercury, copper, tin, tungsten, lead, zinc, antimony, arsenic, bismuth, nickel, cobalt, chromium, manganese, and iron. Of these gold takes the lead in cash value, iron coming next, if we reckon the price at the mine, though the value of the manufactured iron far exceeds that of the gold.

Gold occurs either as the native metal, or as telluride, or in solid solution in various sulphides. It forms no other natural compounds. The primary ore of silver is apparently the sulphide, argentite; but this is not a very important ore. Most silver is obtained from argentiferous galena or from a large number of complex silver ores containing antimony, arsenic, sulphur and other elements found in the zone of secondary enrichment; native silver and silver chloride are also important ores. Platinum occurs as the native metal in serpentines and in alluvial deposits derived from serpentines. Platinum is also obtained from the residues in the smelting of other metals. Mercury is found as sulphide, cinnabar, either in mineral veins or as a dissemination in sandstones and limestones. The chief primary ore of copper is chalcopyrite or copper pyrites; this when oxidised and reprecipitated as before described forms secondary sulphides, often complex, carbonates, and native copper. Tin is found chiefly as the dioxide, cassiterite, in lodes and veins and to a small extent as stannite, a complex sulphide containing also lead, zinc, and iron. Alluvial tin is very important. Lead and zinc generally occur together, the primary ores being the sulphides galena and zinc-blende; the commonest oxidised ores are lead carbonate, cerussite ($PbCO_3$), and the carbonate and silicate of zinc. Antimony and arsenic form sulphides and a large number of complicated minerals, in many of which the antimony and arsenic act as acid-forming elements, commonly as sulphantimonides and sulpharsenides. Bismuth occurs native and as sulphide and other compounds. Nickel and cobalt combine with sulphur and arsenic, and also occur as oxidised minerals derived from the sulphides and arsenides. Manganese forms a large number of different oxides, also carbonate; most of these seem to be formed by oxidation of primary silicate. Iron is known in the native state in meteorites alloyed with nickel, and in one or two terrestrial localities in basalts; but the sole practical sources are various oxides, silicates and carbonates, which may be of igneous, metamorphic, or sedimentary origin. The genesis of the chief types of these

deposits has already been described in some detail. There are also certain metals used for special purposes that are exploited in comparatively small quantities, such as tungsten, molybdenum and vanadium, used for hardening steel, and the metals of the rare earths, used for incandescent gas-mantles. Tungsten is also the material of the ordinary electric lamp filaments. Chromium occurs chiefly as chromite, often along with platinum, in ultra-basic igneous rocks; tungsten and molybdenum chiefly belong to the pneumatolytic phase of granite intrusions; while the metals of the rare earths are found primarily in granites and pegmatites and secondarily in sands formed by natural weathering of such rocks.

CHAPTER XIV

THE PRINCIPLES OF STRATIGRAPHY

To a large extent the previous chapters have been devoted to the consideration of the records of past events furnished by a study of the earth's crust. It is the special function of stratigraphy to discover and arrange these records, and, with the aid of other branches of the science, to decipher their meaning.

It was amongst the newer rocks that the science of stratigraphy arose. In the more ancient parts of the earth's crust the stratification is often far from clear, and the rocks are frequently so altered that their origin is obscured. To the unaided eye there is nothing in a slate to suggest that it was once a mud, or in a quartzite to show that it was ever a bed of sand. It is otherwise with more modern rocks. The stratification is generally distinct, and the beds themselves are often similar to deposits now to be seen in process of formation. The clays are not unlike the muds of existing rivers, and many of the sandstones are evidently compacted sands.

The Law of Superposition.—As soon as it was realised that the stratified rocks were *deposits*, the foundations of the science were laid. For at once it followed that in all normal cases each bed is older than the one that lies upon it, and newer than the one on which it rests. And this is the fundamental principle of stratigraphy. It is often called the law of superposition.

The law assumes that the beds were laid down one upon another, and it does not hold excepting when the stratification is due to deposition. An intrusive sill may to all appearance be a bed, but it is not older than the bed that lies upon it. The foliation of a gneiss or schist may simulate stratification; but it is not due to deposition; and the law of superposition does not apply.

It is only occasionally that such cases lead to any serious difficulty; and generally, in any single section, such as a quarry or sea-cliff, it is easy to determine the order of succession of the strata, and consequently their relative age. But to do this even in a hundred sections would be of little value unless there were some means of linking together or correlating the sections. If, however, it is possible to show, for example, that bed 6 at the top of section A is the same as bed 1 at the bottom of section B, then we know that the beds in B are the continuation of the series of which a part is shown in A. And if, in a similar way, the

correlation of the beds can be continued from section to section, the complete succession throughout a whole district may be determined.

The correlation of the various sections is carried out in several ways. In a region that is destitute of vegetation and bare of soil, the outcrop of some particular bed may be seen to pass from one section to another. In a country such as England, where the rocks are generally concealed, the process is not so easy. Some of the beds, however, will be harder than the rest; and usually a hard bed will protrude at intervals through the soil, or its outcrop will form a ridge that can be traced, although the rock itself is hidden. Sometimes there may be a bed of such peculiar character that it can be recognised at once. In that case, even if it be not visible in the intervening country, it will serve as a datum line for the comparison of the sections in which it occurs. But however remarkable the bed may be, it is always possible that there may be others of the same kind in the district, and care is therefore necessary in making use of this method.

Apart from the complications introduced by folds and faults, the chief difficulty in the application of the law of superposition arises from the fact that deposits change their character laterally. When a limestone lying between two beds of shale is traced across the country, it often happens that layers of shale appear within it. Gradually the shales thicken and the limestone thins, until at last the whole series becomes a mass of shale. It may be quite impossible to say how much of the shale represents the original bed of limestone.

Nevertheless, the law of superposition will generally enable a geologist to determine the order of succession in any particular district with a fair degree of accuracy. Sometimes, however, it fails; and evidently it does not help him to compare the rocks of one region with those of a distant and disconnected area. But when the direct application of the law becomes impossible, palaeontology lends its aid.

Correlation by means of Fossils.—In the early part of the nineteenth century it was shown by William Smith, an English surveyor and engineer, that each bed or group of beds is characterised by a definite set of organic remains. It can be recognised by its fossils at least as readily as by its lithological nature. In fact, the fossils are a safer guide than the lithology, for deposits of very different age may be remarkably alike.

The discovery of this principle led to far-reaching results. It then became possible to correlate the rocks of England with those upon the Continent; and, as time went on, the correlation was extended even into the most distant parts of the globe. Gradually the stratified rocks were arranged in order, and a complete scheme of classification was evolved upon the plan initiated by William Smith.

The full development of the method of correlation by means of fossils was hardly possible until the doctrine of evolution had been

formulated. As long as species were looked upon as separate creations, the laws which govern their distribution could scarcely be understood; and indeed they cannot be completely understood until our knowledge of the laws of variation is less imperfect than it is at present. But the first principle of stratigraphical palaeontology may be stated thus: Every species, whether of plant or animal, lives only for a limited period upon the earth and then dies out; and once extinct, it never reappears.

A similar statement might be made concerning individuals, and the two statements rest upon the same kind of evidence. The first part scarcely requires any further remark. With regard to the second part, it should be noted that in any limited area a species may disappear and reappear, not only once but many times in succession. If the conditions become unfavourable, it withdraws; and returns with the return of the conditions that favoured it. But all the evidence goes to show that if a species becomes extinct throughout the globe it never reappears.

If we imagine the whole series of stratified deposits arranged in a column in order of age, each species will therefore have a certain vertical range (often called its range in time); and any bed in which it occurs must lie within that range. The vertical range may be great or small; and the smaller it is the more exactly does the occurrence of the species fix the stratigraphical position of the bed in which it is found. But there are many difficulties in the application of this principle. It is not possible to define precisely what constitutes a species. The term is artificial, and is used by some authors in a much more restricted sense than by others. Sometimes it can be shown that one species passes into another by a series of almost imperceptible gradations. Whether this was always the case remains to be proved; but many species had no definite beginning and no definite end, and their vertical ranges accordingly are also ill-defined.

The vertical range of a species is not exactly the same in all parts of the world. A species begins in some particular district, and from there it spreads. At some period in its life it attains its maximum development, and then it dies out gradually or suddenly. It does not necessarily survive latest in the area in which it originated.

This is shown diagrammatically in Fig. 101, which is a 'distribution-diagram' of an imaginary species. The ordinates represent time and the abscissae space. A, B, C, D, are different localities.[1] The base-line denotes the date at which the species began, and the spaces between the horizontal lines represent equal periods of time. The species originates at C. At the end of the first period it has spread from A to D. It then begins to die out, and after living for three periods, disappears at B.

[1] For simplicity these points are supposed to be in the same straight line. An actual distribution-diagram should be in three dimensions.

If our first observations were made at C, the species would be found only in the deposits of the first and second periods. If the species were subsequently discovered at B, it would naturally be assumed at first that it belonged to one of these two periods, whereas it may really belong to the third.

Accordingly, even if we know exactly the vertical range of a certain species in England, the discovery of the same species in Australia does not prove that the deposits lie within the same range. But the distribu-

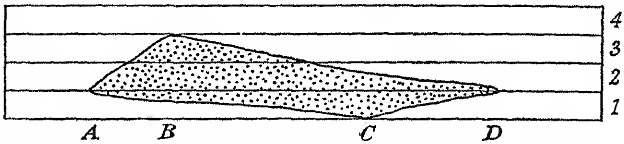


Fig. 101.—Distribution-diagram of an Imaginary Species.

tion-diagram is not likely to be identical for any two species; and therefore the greater the number of species common to the Australian and the English deposits, the greater the probability that they are of approximately the same age.

It is not possible to construct a distribution-diagram of an actual species with any approach to accuracy. Periods of equal length may be represented by very unequal thicknesses of deposit, and there is no geological measure of time. But the imaginary diagrams in Fig. 102 show the general nature of the differences which undoubtedly exist between different species in respect of their distribution; and a com-

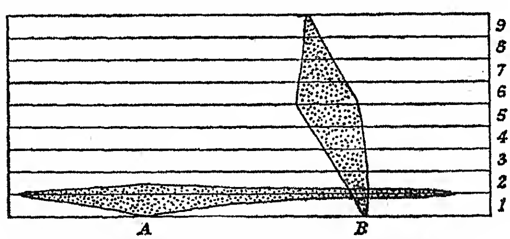


Fig. 102.—Distribution-diagrams of Species.
A, Useful for purposes of correlation; *B*, Of little use.

parison of the diagrams will show why some groups of animals are of much greater value in stratigraphy than others.

In order that a species may be useful for correlation, it should fulfil the following conditions:

1. Its total vertical range should be small. In general this implies that it must belong to a group in which evolution is proceeding rapidly. New forms are quickly being produced and quickly replace the species from which they are derived.

2. It must be easily and rapidly distributed, so that the interval between its origin and its maximum extension may be short. On *a priori* grounds, marine forms which are either floating or free-swimming for at least a portion of their lives may be expected to fulfil this condition most completely.

3. Its maximum extension must be considerable. A form which always has a limited geographical distribution can only be of local value.

Of all the groups of animals that have existed on the earth, the most useful, owing to the wide geographical distribution of the species and their small vertical range, have been the trilobites and graptolites in the older Palaeozoic rocks, the ammonites in the Mesozoic beds, and the foraminifera in the Tertiary. The last have proved very useful in oil geology.

But however wide the distribution of a species may be, there was never one, we may well suppose, that overspread the whole earth. Every species has its limitations. Some can live only on the land, others only in the water. Some require fresh water, others salt water, Some dwell in the deep oceans, others on a shelving shore. Some need a sea that is free from sediment, others flourish only where the rivers bring down mud from the neighbouring land.

Consequently the fossils in a bed depend not only on the time when it was formed, but also on the conditions under which it was deposited. A limestone and a clay, even if they belong to the same period, will usually contain more or less distinct faunas. When a geological series or system is in one district composed chiefly of limestone and in another of clays and shales, it is usual to speak of these different types of deposit as different 'facies.' Thus we may have a calcareous facies and an argillaceous facies of the Lower Carboniferous. Or the facies may be named after the predominant element in its fauna. In the Ordovician system we may recognise a graptolitic facies, in which the principal fossils are graptolites, and a shelly facies, in which brachiopods and other shells abound.

Fortunately there are forms that can adapt themselves to various conditions, and usually the different facies of a geological series will have some species in common. Moreover, the change from one type of deposit to another is generally more or less gradual, and where the change takes place there will be a certain amount of interstratification of the two facies.

In innumerable instances it has been found that a well-marked lithological division when traced across country is found to contain fossils of different zones, thus showing that it was formed in either a rising or a sinking area, the facies-lines therefore cutting across the time-lines. This is called diachronism.

Classification of the Stratified Rocks.—As the order of the stratified rocks was gradually made out, it became necessary, if only for conveni-

ence, to divide them into groups. The divisions that were first adopted were based upon lithological characters. There is, for example, in the Midland counties, a group of red sandstones and marls followed by a series of dark clays with occasional bands of limestone. These were recognised as two distinct divisions. The former was named the New Red Sandstone and the latter the Lias. But as the study of the science proceeded, it became evident that lithological divisions are unsatisfactory, and more and more importance was attached to fossils.

Often the passage from one set of beds to the next is very gradual, and the fauna also alters gradually; but sometimes there is a rapid change of character either in the deposits or in the fossils, or in both; and occasionally there is an actual break or interruption of continuity, and the beds and fossils above are quite distinct from those below. Some of the breaks are purely local, but others extend over a very wide area. Most of them are marked by unconformities; but sometimes the unconformity is very slight, and occasionally there is no unconformity at all.

The more widespread and important breaks are taken as dividing lines; and dividing lines are also drawn where the fauna and lithology change rapidly, even though there may not be any real interruption of continuity. In this way the rocks of the earth's crust have been divided into four great divisions, which are often known as groups. The groups are subdivided into systems, the systems into series, and the series into stages.

According to the scheme usually adopted, the groups and systems are as follows (in descending order):

GROUPS	SYSTEMS
Kainozoic or Tertiary	Neogene. Palaeogene.
Mesozoic or Secondary	Cretaceous. Jurassic. Triassic.
Palaeozoic or Primary	Permian. Carboniferous. Devonian or Old Red Sandstone. Silurian. Ordovician. Cambrian.
Precambrian.	

Note.—The Kainozoic Group is often split into five divisions, viz. in descending order, Pleistocene, Pliocene, Miocene, Oligocene, Eocene. These are sometimes called Systems, but are more commonly looked upon as Series. As will appear later, the Permian and Triassic Systems are combined into one in this book, under the name of New Red Sandstone, and the division between Palaeozoic and Mesozoic is ignored, since in Britain it does not correspond to a break in the succession.

The systems are far from equal in thickness. Their development varies from place to place; but in Great Britain generally most of the Palaeozoic systems are considerably thicker than those of the Mesozoic and Kainozoic groups.

Because, in the scheme of classification, the strata are arranged in order of deposition, the names which are applied to the subdivisions may also be applied to the periods of their formation. Thus we speak not only of Palaeozoic rocks or beds, but also of Palaeozoic times. The term Cambrian signifies not only the deposits belonging to the system, but also the period during which the system was deposited. Conventionally the period of formation of a group is called an era; a system corresponds with a period; a series with an epoch; and a stage with an age. But few geologists adhere rigidly to this convention.

Two other terms in common use require a few words of explanation. A zone is a layer of deposit, of limited but variable thickness, characterised by a very definite assemblage of species, which distinguishes it from all other deposits. Usually one or more species are either confined to the zone or are abundant in the zone and rare outside its limits. The zone is named after one or more of these characteristic species. Thus we speak of the *Rastrites maximus* zone, the *Ammonites margaritatus* zone, the *similis-pulchra* zone, etc. When a zone is clearly defined, we may safely assume that wherever it is found the deposits which form the zone were approximately contemporaneous.

The term horizon is used to denote a definite position in the scheme of classification. Theoretically it represents an actual date, just as a system represents a period of time. When we say that a certain bed in England is on the same horizon as a certain bed in America, we mean that they were formed at the same time. In theory the boundaries between the various systems are definite horizons. In England it is customary to include in the Cambrian system certain deposits which on the Continent are usually placed at the bottom of the Ordovician system. This is expressed by saying that we draw the boundary at a somewhat higher horizon than the Continental geologists.

Since the principle of correlation by means of fossils was discovered in England, it was in England that the first outlines of the modern scheme of classification were sketched, and the boundaries between the systems were drawn at the horizons that seemed most natural in Northern Europe. But as the study of stratigraphy was extended into distant lands it was found that a system which in Europe is sharply limited, in another region may be vague and ill-defined. Changes in the fauna and in the nature of the deposits are caused by changes in conditions, and these changes are not contemporaneous throughout the globe. A break is a natural line of division wherever it is found; but breaks do not everywhere occur at the same horizons.

A break indicates that an interval of time is unrepresented by

deposit. It may be simply that no sediment was laid down where the break occurs. This may happen, for example, if the rivers or currents that brought the sediment were temporarily deflected; but such a break is not likely to be widespread or of long duration. More often a break is due in part to the removal of material that has already been deposited. Generally it means that for a time the area was land, but sometimes the denudation was accomplished on the floor of the sea by an increase in the strength of wave action. In any case the material that is removed must be deposited elsewhere, and consequently a break in one area implies deposition in some other region, and a universal break is almost an impossibility. In England there is a strongly marked break between the Carboniferous and the Permian; in the East there is a perfect passage. And many other similar examples might be given.

A rapid change in deposits or fauna, without any actual break, may be brought about in several ways; but always it implies an equally rapid change of conditions. An arm of the sea may be cut off and converted into a lake, and in a short time the lake will usually become, according to circumstances, either salter or fresher than the open ocean. In either case the change of conditions will be reflected in the deposits and the fauna. A change of the opposite kind is likely to be still more sudden. When the sea breaks into a fresh-water lagoon, most of the original denizens will quickly die and their place will be taken by invaders from the sea. In such ways as these may be produced sudden transitions from one type of sediment to another, without any interruption of continuity. But evidently such changes cannot be universal. Since neither breaks nor rapid changes are universal, it is evident that the limits of the systems are necessarily arbitrary. If natural in one region they must be unnatural in another; and accordingly we find that there are difficulties in applying the European classification in many parts of the world.

Geological History.—As the object of stratigraphy is to decipher the history of the earth, it is not sufficient to determine the succession of the rocks and to arrange the fossils in order of antiquity. This is the first step only. The next is to deduce the conditions that prevailed during different periods. The method of procedure is to compare the rocks with the deposits of the present day, and the fossils with the animals and plants that now inhabit the globe.

The characters of the deposits formed under different conditions have been described in previous chapters, and no further reference is needed here. The study of the fossils is properly the province of Palaeontology, but a few general observations on the evidence which they afford may be useful.

Terrestrial forms are often easily distinguished. The teeth of land mammalia, the wings of insects, the fronds of ferns and the leaves of

trees can generally be recognised as such even by the untrained eye. But other remains are not always so characteristic, and it may require a specialist to determine whether they belong to terrestrial or aquatic forms. It is worthy of notice that the only land Mollusca are gastropods, and the shells, when they possess shells, are always holostomatous, and generally rather thin.

When terrestrial forms occur alone, the bed in which they are found was deposited, presumably, upon the surface of the land itself; but when they are associated with aquatic forms their presence only proves that land was near.

Terrestrial deposits are rare, and usually the question that arises first with regard to any bed is whether it was fresh-water or marine. Radiolarians, corals, echinoderms, brachiopods, pteropods and cephalopods are now found only in the sea, and the presence of any of these may be taken as a sure indication that the deposit was marine. Foraminifera and sponges are almost equally conclusive. Graptolites and trilobites are now extinct, but their associations with other forms show that they were marine. Lamellibranchs and gastropods occur both in the sea and in fresh water; but the number of fresh-water forms is comparatively small, and the fresh-water gastropods are generally distinguished by possessing a thin and fragile shell.

When it has been shown that a deposit was marine, it is desirable to determine whether it was laid down in deep or shallow water; and this is often a matter of considerable difficulty. At present many genera live only at certain depths, but it is doubtful if their ranges were equally limited in the past. The evidence afforded by groups of animals rather than by genera is sometimes of more value, but even this is often doubtful.

In many cases deposits consisting largely of foraminifera or radiolaria have been taken as indicative of deep waters. But they are evidence of clearness rather than of depth: where sediment is abundant such very minute shells are lost in the thickness of deposit. A somewhat similar observation applies to all floating forms that are not affected by the depth of the water beneath them: their remains will be relatively most abundant where the sediment is least. Graptolites have been supposed to point to a considerable depth, but whether they were floating forms or not, they follow the same rule. They are most abundant where deposition was slow, but they occur occasionally in sandstones and other rapidly formed deposits. Reef-building corals, in the past as in the present, appear to have been confined to shallow water. Of the Mollusca it may be said generally that the shallow-water forms possess thick shells, and those that live at great depths, as well as those that float upon the surface, have thin ones; but to this rule there are exceptions.

From the fossils that are found in a deposit it is sometimes possible

to infer the climate that prevailed when it was formed. In the London Clay, for example, leaves of palms and other tropical plants occur, together with turtles, crocodiles and other animals now living only in warmer latitudes. Hence we may reasonably conclude that when the London Clay was deposited, the temperature of the area was considerably higher than it is at present. At the close of the Pliocene epoch, on the other hand, the dwarf willow and dwarf birch grew in England, which shows that the climate was arctic in its severity.

Plants are in general more useful in this respect than animals, because their distribution is usually more strictly limited by climatic conditions. But whether plants or animals are our guides, the conclusions that may be drawn from them are most trustworthy in the case of the more recent beds, for in these the fossils are most closely allied to the forms that now inhabit the earth. In the older rocks the types become so different that their evidence is less decisive. In modern seas reef-building corals require a mean temperature not less than 68° Fahr. It is probable, therefore, that coral-reefs in ancient rocks also indicate a warm sea; but the inference is open to doubt, for the older corals differ in structure from the modern forms, and they may have differed in habit.

Astronomical considerations suggest that even in the Palaeozoic era the climate cannot have been uniform throughout the globe; and several attempts have been made to show that the northern faunas differed from the southern. In the Ordovician and Silurian systems, for example, there are many trilobites common to England and Scandinavia, but unknown in Bohemia; and many Bohemian forms are not found in the north of Europe. But there are other causes besides climate which influence distribution, and it is difficult to disentangle their effects. A barrier between two seas will prevent the faunas from mixing, or the variations may be due to difference in depth or other conditions.

The absence or rarity of fossils indicates either that the conditions were unfavourable to life or that they did not lend themselves to the preservation of organic remains. By itself it does not lead to any certain conclusions; but when the rarity of fossils is associated with the presence of deposits of salt, wind-blown sands, etc., as in the Trias, we may infer that desert conditions prevailed. When the unfossiliferous beds contain glaciated boulders, an arctic climate is suggested.

Geological Time.—Many attempts have been made to form an estimate of the duration of geological time in years, but all of them rested on very slender bases, and have now been shown to be unreliable, with one exception, which shows some promise. This depends on the phenomena of radioactive disintegration of heavy elements, especially uranium and thorium, whose ultimate product is lead. The methods cannot be described here: it will only be stated that this line of work

suggests ages of about 30 million years for the base of the Tertiary, 240 million for the Carboniferous, 400 million for the middle of the Lower Palaeozoic and 1,500 million for the Archaean. Another method based on helium, not yet widely applied, gives consistent values of about half the above, so that it can only be said that we have some idea of the probable relative ages of the different systems and of their order of magnitude.

Maps and Literature.—In the study of stratigraphy it is important that the student should obtain a clear idea of the distribution of each system. The maps given in the text are intended to assist him; but he should also make constant use of the geological map of the British Isles published by the Geological Survey. For further details he may refer to the Geological Survey Index Map of England and Wales on the scale of four miles to the inch, now published in twenty-five sheets. He will find it helpful to procure the particular sheet in which his own district is situated. The one-inch maps of the Geological Survey give still fuller information.

Owing to the amount of detail, very few stratigraphical papers in geological journals are suitable for the elementary student's reading. Until he has fairly mastered the following pages he may be recommended to confine his outside reading to works that deal with his own district. For this purpose the series *British Regional Geology*, published in about 18 parts by the Stationery Office, will be found excellent. Each part deals with a definite geographical region of Great Britain, and contains a bibliography. A more general account will be found in larger works, especially the *Handbook of the Geology of Great Britain*, edited by Evans and Stubblefield, and published by T. Murby and Co., London. This work, though abounding in detail, is somewhat weak on the structural and palaeogeographical side. For this *The Physiographical Evolution of Britain*, by L. J. Wills (Edward Arnold & Co., London) will be found most useful.

CHAPTER XV

THE PRECAMBRIAN SYSTEMS

The oldest known definitely fossiliferous beds form the Cambrian system, but beneath them lie a vast mass of rocks in which no fossils have yet been found. These are most conveniently known as Precambrian, though many other names have been suggested, for the most part quite unnecessarily. In various places remains of organisms or indirect evidence of their existence are said to have been found, but none of this evidence is so far conclusive. In the nature of things it is obvious that the Precambrian rocks can have no base: they must pass down gradually and indefinitely into the lower zones of the earth's crust. Hence, unlike the rest of stratigraphical geology they can only be investigated by working downwards, with the base of the Cambrian as a datum line. In the British Isles this horizon is everywhere marked by a pronounced unconformity, and where the Cambrian is not present and the oldest fossiliferous rocks are of later date there is rarely any difficulty in recognising the junction between them and the Precambrian, the chief criteria being lithological character and degree of metamorphism.

In many large regions of the world, the ancient continental blocks which consist mainly of Precambrian rocks, it is found that there is a more or less clear division into two types: the upper and newer Precambrians consisting of comparatively unaltered sediments, the older series, extending indefinitely downwards, being mainly in a crystalline condition, as gneisses and schists. For this lower group it is convenient to use the name Archaean (which, however, has unfortunately been defined in other senses), while the newer type is in America and elsewhere commonly known as Algonkian. Of these two types the Lewisian and Torridonian series of north-west Scotland, to be defined shortly, afford admirable examples. Both the Archaean and the Algonkian groups include in many places large developments of igneous rocks, also showing different degrees of metamorphism.

It is impossible to give here an adequate description of the Precambrian rocks: any but the most general treatment must involve a knowledge of petrology and metamorphism such as cannot be expected from elementary students, and moreover there are in the Precambrian of Britain and especially of the Scottish Highlands many difficult problems that are still the subject of controversy.

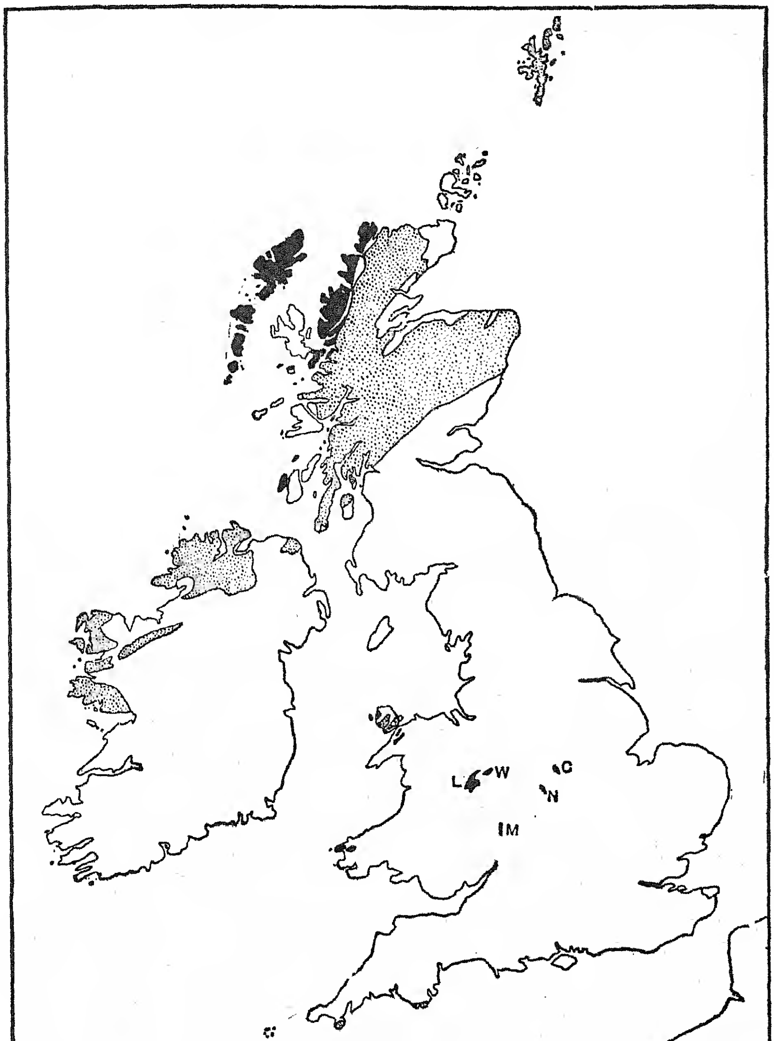


FIG. 103.—MAP OF THE PRECAMBRIAN ROCKS.

Undoubted Precambrian outcrops—black; doubtful outcrops, and areas which consist of Precambrian and later rocks folded together—shaded

W, The Wrekin; *L*, The Longmynd; *M*, The Malvern Hills; *N*, Nuneaton; *C*, Charnwood Forest.

In the British Isles the largest area of Precambrian rocks is in the north. A narrow strip along the coast of Sutherland and Ross and almost the whole of the Outer Hebrides consists of undoubted Precambrian rocks, while the rest of the Highlands is certainly largely composed of rocks of that age. Smaller tracts occur in North and South Wales, Shropshire and the Malvern Hills. Isolated masses also rise through the newer rocks of the Midlands and in West Yorkshire. The rocks of the Start Point in Devon and the Lizard in Cornwall are almost certainly Precambrian.

The Precambrian systems include rocks of three distinct types: gneissose or schistose; volcanic; and sedimentary. The gneissose type is believed to consist largely of metamorphosed plutonic masses, though including some sediments; the volcanic type is formed of lavas and ashes, often also much altered; while the third type consists of more or less unaltered sediments.

It is uncertain how far these types represent distinct periods; but there can be little doubt that in general the gneissic rocks are the oldest. They have suffered by far the highest degree of metamorphism, and in Scotland they are overlain unconformably by arkoses and grits of the sedimentary type. The relative age of the volcanic rocks has not been determined with the same certainty. They generally occur in separate areas, and it is possible that the sedimentary deposits were laid down in one region while at the same time the volcanic rocks were erupted in another. In Scotland, however, pebbles of rhyolitic lava are commonly found in the sedimentary series, and hence it may be inferred that there must have been an earlier volcanic series from which the pebbles were derived. In Shropshire both the sedimentary and volcanic series are present, but separated by faults so that their relations to each other are obscure. The sedimentary series, however, contains fragments of lava which appear to have been derived from the volcanic series.

It is clear then that the Precambrian rocks of Britain represent three distinct facies, the gneissose types being the oldest: the relative ages of the other two are uncertain.

They are shown in the following table, with typical examples of each.

Sedimentary facies . . .	Torridonian and Longmyndian.
Volcanic facies . . .	Uriconian and Charnian.
Gneissose facies . . .	Lewisian and Malvernian.

The names in the second column will be defined later in this chapter. Of these facies the first is Algonkian, the last Archaean in the American sense. The relative ages of the first and second are probably variable in different areas.

Scotland

Precambrian rocks occupy a strip of country on the western coast of Sutherland and Ross, extending from Cape Wrath on the north to Loch Alsh in the south ; into the Isle of Skye ; and as far as Islay, and they also occupy most of the Outer Hebrides. Two divisions are clearly represented, the Lewisian gneiss and the Torridonian. No volcanic series is met with, but pebbles of lava are found in the Torridonian. In many places basal Cambrian beds rest unconformably on both the Torridonian and the Lewisian, so that the age of these rocks is indisputably established.

The **Lewisian Gneiss** may be divided into (*a*) a 'Fundamental Complex' and (*b*) a series of igneous rocks intruded into the complex as dykes and sills.

The Fundamental Complex is a mass of gneisses and schists of various composition and of varied structure. Owing to subsequent earth-movements and metamorphism it is not possible to separate the individual members. Even the later dykes and sills have sometimes been converted into schists and incorporated indistinguishably into the complex. But on the whole the schists appear to be metamorphosed sediments, and the gneisses metamorphosed plutonic masses. The former are relatively of small importance, and are found chiefly in the valley of Loch Maree. The latter form by far the greater part of the complex. They vary in composition from ultrabasic to acid, the basic portions being earlier than the acid. Usually they are banded or foliated, but not uncommonly the structure is on so large a scale that it is not visible in hand-specimens, and sometimes it entirely disappears and the rocks become indistinguishable from an ordinary plutonic mass. The banding and foliation appear to be due chiefly to three causes : (1) differentiation of the ferro-magnesian and quartzo-felspathic constituents while the rock was still molten and flowing ; (2) intrusion of the residual molten matter into the parts which had already solidified ; (3) earth-movements after consolidation.

Of the dykes and sills intruded into the Fundamental Complex, a small proportion are post-Torridonian in age and need not be considered here. But by far the greater number were intruded before the Torridon Sandstone was laid down. Like the gneiss itself, they vary in composition from ultrabasic to acid. The ultrabasic dykes usually trend from E. to W. and are comparatively of small importance. The basic dykes, mostly dolerites, occur in extraordinary numbers, especially between Loch Laxford and Enard Bay, and generally run from W.N.W. to E.S.E. The acid intrusions, both sills and dykes, are also very abundant, and consist for the most part of granite and pegmatite. The basic dykes appear to be the oldest of the series.

These intrusions evidently took place after the Fundamental Com-

plex as a whole had solidified, and they were subsequent to the primary banding of the mass; for in many places, while themselves unfoliated, they traverse banded gneiss. At a later date, but still before the Torridonian sandstones were deposited, earth-movements took place, accompanied by shearing along planes running from E. to W. or E.S.E. to W.N.W.; and along these planes the dykes are themselves converted into schists.

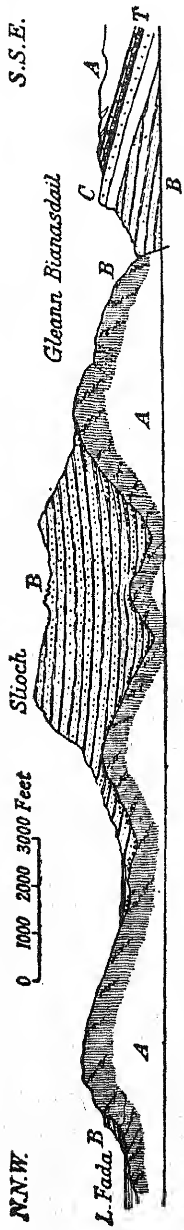


Fig. 104.—Section from Loch Fada across Slioch to Gleann Bianasdail.
(From *Memoirs of the Geological Survey*, 'The Geological Structure of the North-west Highlands.' Reproduced by permission of the Controller of H.M. Stationery Office.)

A, Lewisian Gneiss; *B*, Torridon Sandstone; *C*, Cambrian; *T*, Thrust-plane.

The **Torridonian** series is a stratified deposit, which throughout the greater part of its extent rests horizontally or with a gentle dip upon the Lewisian rocks (Fig. 104). No sign of the great disturbances affecting the latter is to be found in the former, and the Lewisian gneiss must have attained its present features before the sedimentary series was deposited. If the Fundamental Complex was originally a deep-seated plutonic mass, the whole of the overlying rocks must have been removed before the Torridonian series was laid down, and the interval of time represented by the unconformity between the two must be enormous.

The greater part of the Torridonian series consists of red felspathic grits and sandstones (arkose), generally coarse in texture, but with occasional thin beds of fine-grained micaceous shale and sandstone. Where they rest upon the older rocks an angular breccia is often found, and bands of conglomerate occur at different horizons. The whole series is characterised by false-bedding, and appears to have accumulated quickly. A remarkable feature is the freshness of the felspar grains, which has led to the suggestion that disintegration must have been more rapid than is usual in a temperate climate.

Although red is the predominant

colour of the formation and the texture is generally coarse, neither colour nor texture persist throughout the series. Especially towards the top and bottom shales occur in some localities, together with occasional calcareous bands. But these shales were not laid down in deeper water, for, in the lower division at least, their surfaces are marked with rain-pittings and sun-cracks. In the upper shales black phosphatic lenticles have been found, probably indicating the presence of organisms; but the nature of the organisms is not clear, and no other sign of life has been discovered.

The actual basement is usually a coarse conglomerate formed of fragments of the Lewisian gneiss from the immediate neighbourhood. In general however, the material of the greater part of the series is not derived from any rocks existing on the mainland.

The surface on which the Torridonian series rests is very irregular. It has the form of an undulating plateau carved into mountains and valleys; and the Torridonian deposits fill the valleys and spread over the hills. The height of some of the hills was certainly not less than 2,000 feet, and probably many of them were considerably higher. In some cases, by the removal of the sandstones, the actual Torridonian landscape is exposed to view and the present rivers follow the course of the old valleys.

Much of the material of the Torridonian series is well-rounded, and must have been laid down by water. The false-bedding shows that the currents which bore it were variable in direction and strength, and the size of the pebbles indicates that at times their force was great. But since the deposits fill the valleys, it is evident that in the lower ground the currents ceased or their velocity was diminished, and they were unable any longer to carry the material which they had brought. The deposit, in short, is of torrential origin. It was washed down by mountain streams and laid upon the valley floors, where the waters spread and lost their force. It has already been remarked that the freshness of the felspars indicates a rapidity of disintegration greater than is usual in temperate climates, and it has been suggested that this was due to the action of frost.

So vast an accumulation of horizontally bedded deposits, burying hill and valley indiscriminately, finds no parallel at the present day except in the drier regions of the globe, such as the 'dasht' of Baluchistan and Afghanistan. In these there is the same rapidity of disintegration of the solid rock and accumulation of loose material. At certain seasons heavy floods sweep the loose débris down the mountain-sides and spread it far and wide over the plains and valleys; but the intermittent nature of the rainfall prevents the establishment of permanent river-courses carrying the material to the sea.

Between the eastern boundary of the Lewisian-Torridonian area (the outcrop of the Moine Thrust) and a line drawn from the mouth of the

Clyde to Stonehaven (the Highland Boundary Fault) the whole of Scotland is underlain by a great series of intensely altered rocks, and the same extends far into Ireland. Parts of this at any rate are undoubtedly Precambrian, but detailed interpretation is rendered very difficult by the fact that the area has been affected by intense earth-movement and metamorphism at two distinct periods, the first Precambrian, the second Devonian (see also Chapter XXVII). The result is that the structures are extraordinarily complex, and the controversies that have arisen as to their interpretation are far beyond the scope of an elementary textbook.

Many of the rocks were originally ordinary clastic sediments, sandstones, shales and limestones, together with volcanic rocks, all invaded by great plutonic intrusions and subjected to intense dynamic metamorphism. Hence many of the rocks are high grade gneisses and schists. The later intrusions, which are not gneissose, are described briefly in Chapter XXVIII.

As a very broad subdivision the rocks of the area between the Moine Thrust and the Caledonian Canal are called the Moine series, while the southern Highlands are occupied by the Dalradian series, which includes quartzites and limestones in Perthshire (and also in Donegal). The relative age of these groups is still uncertain and it is not yet definitely known how far they include altered Lewisian and Torridonian rocks. There are patches like the Moines in the southern Highlands, and at the southern boundary some Lower Palaeozoic fossils have been found close to the fault, so that rocks later than Precambrian may be included in the more altered areas to the north.

It is at any rate clear that the later (Devonian) earth-movements were of mountain-building type and the structures of the Highland rocks are now of the same general nature as in the Alps and similar great mountain chains, so that it is very difficult to disentangle the earlier history of the area.

Wales

In Pembrokeshire there are several outcrops of Precambrian rocks, all very similar, the best known being that around St. David's. This consists of rhyolitic and trachytic ashes and lavas (the Pebidian series) invaded by acid masses (granite, quartz-diorite and quartz-porphyry) of the Dimetian. The volcanic rocks closely resemble the Uriconian of Shropshire, to be described presently, and may be contemporaneous with them. They were highly folded and deeply denuded before the beginning of Cambrian times.

In North Wales there are two narrow strips of igneous rocks, very like those of St. David's. One extends from Bangor south-westwards to Caernarvon, and the other lies parallel to it some 3 miles to the south. They consist chiefly of ashes, agglomerates and quartz-felsites

with a granitoid mass at Caernarvon. They are overlain unconformably by Lower Cambrian strata.

The largest area of Precambrian rocks is the Mona Complex, which occupies two-thirds of Anglesey. Three principal divisions are recognised. The oldest, the Gneiss Series, consisted originally of coarse-grained plutonic rocks of both acid and basic composition. These suffered intense metamorphism, followed by deep erosion, after which the second, the Sedimentary Series, some 20,000 feet thick, was laid down upon them, along with some contemporary volcanic rocks. They include what were originally sandstones, conglomerates, shales and limestones. Subsequently there was another period of intense earth-movement with much thrusting and inversion, leading to the formation of nappes. Towards the end of these disturbances the third Plutonic Series, of great intrusions ranging from earlier basic to later acid types, came in. As a result of the metamorphism due to both pressure and rise of temperature the Sedimentary Series was largely altered to schists. Some characteristic features of this series are pillow lavas and beds of jasper. Pebbles of the schists and jasper are found in the basal Cambrian conglomerates of the mainland, thereby proving the Precambrian age of the Complex.

Shropshire

The most interesting area of Precambrian rocks in England is in Shropshire, and it is also the most satisfactory, since fossiliferous lowest Cambrian beds are found resting on them, so that there is no doubt of their age. The divisions represented are as follows:

Western Longmyndian or Wentnor Series.
Eastern Longmyndian or Stretton Series.
Eastern Uriconian volcanics.
Western Uriconian volcanics.
Primrose Hill Gneiss and Schist.
Rushton Schist.

The relative ages of these groups are uncertain, owing to faulted junctions, but some Longmyndians are certainly newer than some Uriconians. The Rushton Schists may be Archaean. The Primrose Hill gneisses are probably metamorphosed Uriconians.

A ridge of Precambrian rocks stretches south-westwards from Wellington, forming the Ercal, the Wrekin, Primrose Hill, Caer Caradoc and other conspicuous hills. It consists mainly of volcanic rocks, chiefly acid, called the Uriconian series from the Roman city of Uriconium (Wroxeter). On the flanks of this ridge the volcanic rocks are overlain by a basal Cambrian quartzite followed by the Comley Series with *Olenellus* and other Lower Cambrian fossils. Similar volcanic rocks occur at Pontesford Hill and other points on a parallel line west of the Longmynd. The Wrekin range is bounded on the north-west

by the Stretton fault, so that its relation to the Longmynd is not shown. The structure of this range will be referred to again in more detail in later chapters.

The Longmyndian rocks are nowhere seen to be directly overlain by the Cambrian, but from their entire dissimilarity to anything else in the neighbourhood of later date they may safely be regarded as Precambrian. They form a high moorland tract several miles wide and reach the enormous total thickness of 27,000 feet, or five miles of entirely sedimentary rocks, except for a few very thin bands of tuff. The Eastern division comprises some 10,000 feet of green, grey or purple shales and flags; some beds show what may have been worm-tracks. The Western division consists of 17,000 feet of red and purple sandstones and conglomerates, very like the Torridonians and probably equivalent, as Lapworth thought. The coarser beds contain many fragments of rocks like the Uriconians. The relation of the two sets of Longmyndian beds is not known, but it has been suggested that the Wentnor series is the younger. Both are clearly of Algonkian facies, as they are not metamorphosed.

Malvern

The Malvern Hills have a long narrow north–south core of ancient gneissose rocks, associated with Cambrian strata, the junctions being probably everywhere faulted. There is also a patch of volcanic rocks of Uriconian type, doubtless equivalent to those of Shropshire. The gneisses, which are undoubtedly Archaean and probably coeval with the Lewisian, were originally acid plutonics; diorite, syenite and hornblende-granite. Some at the northern end are hardly foliated at all, but the greatest part may be described as hornblende-gneiss. The tectonic structures of the old rocks appear to be of great complexity, and they have been overthrust on to the partly overturned Silurians of the western border, while on the east the whole is faulted against the Trias. The age of the overthrust is unknown: it can only be said that it is post-Silurian and pre-Triassic and therefore may be either Caledonian or Armorican.

The Midlands

There are three minute outcrops of Precambrian rocks at Lilleshall, near Newport; at Barnt Green, in the Lickey Hills, south of Birmingham; and near Nuneaton. All of these are of Uriconian type. The Nuneaton occurrence, the Caldecote volcanic series, will be referred to again in the chapter on the Cambrian system.

The most important Precambrian rocks of the Midlands, however, are those of Charnwood Forest, which cover about 17 square miles at the surface. They are almost entirely of igneous origin, mainly volcanic, but with some good-sized plutonic intrusions.

The volcanic rocks have been divided into three groups as follows:

Brand series . . .	Slates with some sediments.
Maplewell series . .	Hornstones, ashes and agglomerates.
Blackbrook series . .	Hornstones and tuffs.

The structure is an anticline, striking N.W.–S.E. (Charnian strike) and overthrust inwards by compression from the sides, with much cross-faulting. Associated with the volcanic rocks are several large intrusions, the so-called 'Leicestershire syenites,' which are mostly diorites, (Markfield etc.). Further south, other peaks of similar rock sticking up through the Trias are of the same type and age, and the Mount Sorrel granite may belong here, though it probably does not.

The evidence for the Precambrian age of all these rocks rests partly on their very high degree of cleavage and partly on the finding of boulders of exactly similar rocks in Lower Cambrian conglomerates at Nuneaton.

Yorkshire

At Ingleton and Horton-in-Ribblesdale in West Yorkshire are two small inliers of rocks of Algonkian facies, very similar in many ways, except in colour, to the Torridonian and Longmyndian. The oldest rocks in faulted contact with them are Ordovician, but from their higher degree of alteration there is no doubt that they are of Precambrian age. They are called the Ingletonian Series and comprise about 10,000 feet of slates and grits, with a coarse breccia, often used as road-metal under the misnomer of 'Ingleton Granite.'

Devon and Cornwall

There can be little doubt, though there is no absolute proof, that the rocks of the Start Point in Devon and of the Lizard Peninsula in Cornwall are Precambrian. At the Start the rocks, striking E.–W. consist of (*a*) hornblende- and chlorite-schists; (*b*) mica-schists; and (*c*) quartz-schists. Most of them were originally basic igneous rocks.

The ancient rocks of the Lizard can be conveniently divided into groups as follows. The oldest are the Old Lizard Head Series, of sediments and tuffs, now highly metamorphic and markedly schistose. These were succeeded by a series of basic igneous rocks, now hornblende-schists, and both were then invaded by the Man o' War Gneiss, a granitic rock now visible only as skerries off the Point. The rest of the area consists of a nearly circular mass of igneous rocks, an igneous complex, beginning with great masses of ultrabasic rock, now serpentine, passing on to gabbro and black dykes and ending with the granitic Kennack Gneisses. The whole is separated from the later rocks to the north by a crush-belt of great complexity, rendering its relation to the Ordovician Veryan Series and to the 'Killas' (see p. 348) very obscure.

It is quite clear that during the vast lapse of Precambrian time there must have been several periods of great earth-movement (revolutions). Since, however, it is not possible to correlate Precambrian structures and rocks in widely separated areas there is as yet no means of determining their number. In Britain the best marked is the episode of intense compression that set up a pre-Torridonian N.W.–S.E. strike in the Lewisians. Of late years detailed work has shown that posthumous effects of this early dominant strike have shown themselves at a later date much further south, and it is significant that the Charnian rocks of Leicestershire show this same strike. When strong folds have once been impressed on a rock-series they can never be completely smoothed out again (compare the behaviour of corrugated iron or crumpled paper). It is obvious that a definite grain in the basement rocks of a country is bound to show mechanical effects when subsequent pressures act from different directions on the basement as well as on the later overlying rocks. It is probable that most of the area of the British Isles originally possessed the Lewisian or Charnian grain.

Another point worthy of mention is that in the British Isles Precambrian rocks seem to be poorly represented compared with some other countries. In South Africa, for example, besides the very complicated basement complex there are four or five enormously thick sedimentary systems of Algonkian type, ending with one very like the Torridonian, below the first fossiliferous system. In Canada also there are enormous thicknesses of sedimentary and volcanic rocks, separated by major unconformities and revolutions below the Cambrian, whereas in Scotland there is only the Torridonian, and in Shropshire probably not more than two Algonkian systems, the Uriconian and the Longmyndian, above the Archaean.

The economic products of the British Precambrian are not important. There are some excellent slates at Ballachulish, Easdale, and Aberfoyle in the southern Highlands and the Charnian rocks of Leicestershire are extensively worked for road-metal. In strong contrast to most other countries there is a singular absence of ore-deposits. It may be noted that most of the famous granites of Aberdeenshire, in the Dalradian area, belong to the later Caledonian series of intrusions, not to the Precambrian.

CHAPTER XVI

THE CAMBRIAN SYSTEM

The most definite date-line in British geological history is afforded by the sudden appearance of the oldest fossiliferous strata. Even the earliest known fossils are of a highly organised type, showing great variety, and it is clear that life must have existed somewhere for a long time in more primitive forms. But for some unexplained reason no undoubted examples of these have been found. It has already been pointed out that in many parts of the world, as well as in Britain, the latest Precambrian formations are of the red continental facies, and it seems clear that animal life began in the sea, so that local conditions were unfavourable for the preservation of earlier forms. It may thus be said that accurate stratigraphy with a working time-table begins only with the first fossiliferous formations, that is to say, with the onset of the first definitely known marine period.

This first marine period, the Lower Palaeozoic of the usual classification, included the Cambrian, Ordovician and Silurian. It began with a gradually increasing area of sea up to a maximum, followed by retreat during the later stages as a preliminary to the second continental period, the result of the Caledonian revolution in the Old Red Sandstone (see also Chapter XXVII). So far as the British Isles are concerned, the dominant feature was the formation and subsequent filling of a great geosyncline running S.W.-N.E. across the centre of Great Britain to Scandinavia. In this, marine sediments were deposited without serious interruption to a thickness of something like 35,000 feet. The positions of the original shore-lines are approximately known, and it is the history of the varying conditions within this great gulf that form the chief subject of this and the two following chapters.

As is natural Cambrian rocks are found in Britain in much the same districts as the underlying Precambrian, but the total area is small. The principal outcrops are in North and South Wales; Shropshire; the Malvern Hills; near Nuneaton; in the Lake District; and in the North-west Highlands.

In the British Isles the formation consists chiefly of sandstones and shales, often converted to quartzites and slates. Grits and conglomerates are common at and near the base, but limestones are rare except in North-west Scotland. These characters show that the deposits in the geosyncline belonged at first to the littoral facies and afterwards to

the mud-belt. There are no igneous rocks. Details given in later sections show that sedimentation was not everywhere continuous and that there are local gaps and changes of facies, but not of a high order.

FIG. 105.—THE LOWER PALAEOZOIC ROCKS OF THE BRITISH ISLES.

The calcareous Upper Cambrian of North-west Scotland belongs to a different basin of deposition, with affinities to North America rather than to Europe.

The Cambrian rocks of the geosyncline have been subjected to a high degree of dynamic metamorphism and the finer textured beds are in places converted into high-quality slates. The thickness varies much from place to place : in North Wales, where the succession is best developed, it amounts to nearly 12,000 feet.

The subdivision and classification of the system were originally based upon lithological differences due to change of depth of the sea, but although the changes were widespread they did not take place everywhere at the same time, and for comparison with the rocks of other areas a classification by fossils had to be adopted.

Fauna.—The most remarkable feature of the Cambrian fauna is its complexity. It includes a number of highly specialised forms, the evolution of which from any primordial germ of life must have required many ages to complete. Moreover, it contains representatives of all the *phyla*, or main branches, of the animal kingdom excepting only the Vertebrata. Even at this early date the broad lines upon which, evolution was to proceed were already settled. It is apparent, therefore, that the Cambrian fauna can scarcely represent the advent of life upon the globe ; but few traces of any earlier fauna have been found.

Both in abundance and in stratigraphical importance the brachiopods and trilobites stand in the first rank. The brachiopods are mostly inarticulate, *Lingulella* and *Obolella* being the commonest genera in Great Britain ; but the articulate form, *Kutorgina*, occurs in the lowest division of the formation ; and *Orthis* is abundant in some of the higher beds. Of the trilobites, *Olenellus, Paradoxides, Olenus, Conocoryphe, Ptychoparia*, and many others are entirely confined to the Cambrian. *Agnostus* also is especially abundant, but ranges upwards into the Ordovician. Towards the top, in the Tremadoc rocks, several types characteristic of the succeeding system begin to appear, such as *Ogygia* and *Asaphus* (the latter represented by the primitive form *Asaphellus*). But the trilobites were not the only crustaceans that existed. The Phyllopoda, the Ostracoda and the Phyllocarida were also represented. In the Tremadoc beds are found the earliest forerunners of the graptolites. All of them are branching forms, the most important genera being *Dictyonema* and *Bryograptus*.

But this does not complete the list of the Cambrian fauna. Although their remains are comparatively rare, several other groups of animals are known to have existed. Thus the sponges were represented by the Hexactinellid *Protospongia*. Several classes of echinoderms could even then be distinguished. The earliest-known starfishes and crinoids are found in the Tremadoc beds, while cystideans occur in the Middle Cambrian. The Mollusca are not common, but there were representatives of the three great groups, Lamellibranchia, Gastropoda and Cephalopoda.

Classification of the Cambrian System.—The palaeontological classification of the system is based upon the vertical distribution of the trilobites, and four main groups have been distinguished:

4. Shumardia Series (with Cambrian and Ordovician genera).
3. Olenus Series.
2. Paradoxides Series.
1. Olenellus Series.

These groups have been recognised over a large part of the globe, and therefore have a higher value than any lithological divisions. Each of the four series can be subdivided into zones characterised by individual species, and many even of these smaller subdivisions can be traced over very wide areas. Many continental geologists, however, place the Shumardia series in the Ordovician.

North Wales

It was in North Wales that the Cambrian system was first distinguished, and it is here that the upper part of the formation is best known; but unfortunately the lower beds are in general unfossiliferous.

In Western Merionethshire the Cambrian beds rise to the surface in the shape of a dome, known as the Harlech anticlinal, which is continued westward beneath the sea. The gritty beds near the base of the system form the centre of the dome, while the later beds wrap round them in a series of concentric rings broken open on the west. On the northern side of the dome the Cambrian beds sink beneath the Ordovician rocks of Snowdonia, to appear once more against the Precambrian masses of north-west Caernarvonshire, where they form a broad band parallel to the Menai Straits.

It is in the Harlech anticline (Fig. 106) that the succession is most complete, and there the beds may be grouped as follows:

4. Tremadoc Series . .	Slates.	*Shumardia, Asaphellus, Angelina.*
3. Lingula Flags . . .	Flags and slates.	*Lingulella davisi.*
2. {Menevian Series / Upper Harlech Series}	Grits and slates.	*Paradoxides.*
1. Lower Harlech Series. .	Grits and slates.	No fossils.

As the Upper Harlech Series contains *Paradoxides* the quite conformable lower division probably represents the *Olenellus* division, though there is no definite proof.

The **Harlech Series** is finely exposed in the rugged hills to the east of Harlech, where it is formed of coarse greenish-grey grits and green and purple slates and a curious bed rich in manganese. Though no fossils have been found here, the corresponding beds at the south-eastern corner of the Lleyn peninsula have yielded *Paradoxides* and other fossils characteristic of the second fauna.

The **Menevian Series** consists chiefly of dark slates distinguished

from the overlying Lingula flags by the presence of *Paradoxides* and other fossils of the Paradoxidian series.

The **Lingula Flags** are a series of hard tough sandstones and slates passing upwards, towards the top, into softer slates of finer grain with little or no admixture of gritty material. They have been divided into the following groups:

Dolgelly Beds. Blue and black slates, with *Agnostus trisectus*, *Parabolina spinulosa*, *Peltura scarabaeoides*, *Sphaerophthalmus*, *Orthis lenticularis*.

Ffestiniog Beds. Blue-grey flags and slates, with *Lingulella davisi* and *Hymenocaris vermicauda*.

Maentwrog Beds. Yellow and blue-grey slates and flags, with *Agnostus pisiformis*, *Olenus gibbosus*, *O. truncatus*, *O. cataractes*.

The **Tremadoc Series** consists of greyish slates or shales, somewhat flaggy towards the middle. Near the base is a narrow band crowded with *Dictyonema*, which is found also in Scandinavia and in Russia. The higher beds contain *Angelina sedgwicki*, *Asaphellus homfrayi*, *Shumardia pusilla*, *Macrocystella mariae*, and many other forms.

When next the Cambrian beds appear upon the surface, near the northern border of Caernarvonshire, the total thickness, and especially the thickness of the gritty beds, has considerably decreased. The lower division is formed largely of slates, the Menevian has not been definitely distinguished, and the Tremadoc series and the upper part of the Lingula flags appear to be absent, the Ordovician beds lying directly upon the Ffestiniog group or the lower part of the Dolgelly group.

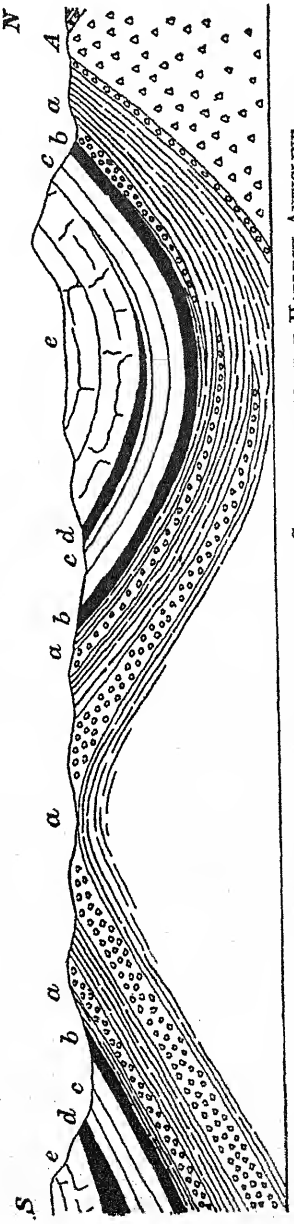


Fig. 106.—Diagrammatic Section from Cader Idris to Snowdon across the Harlech Anticline.
A, Precambrian; *a*, Harlech and Llanberis series; *b*, Menevian; *c*, Lingula flags; *d*, Tremadoc; *e*, Ordovician.

At the base of the whole system is a band of conglomerate which rests upon the Precambrian rocks. This is followed by a series of bluish and purple, occasionally green, slates known as the Llanberis slates, which are quarried extensively at Bethesda (the Penrhyn Quarry), Llanberis, Nantlle, and other places along the band. At the top of the series, where the slates are green, several specimens of a trilobite, *Conocoryphe viola*, have been found in the Penrhyn Quarry. Above the slates is a series of green and grey, occasionally purple, grits, which are well exposed on Bronllwyd.

The Bronllwyd grits are followed by slaty beds which are almost unfossiliferous, but which probably represent both the Menevian and Maentwrog beds of Merionethshire; and these are succeeded by a mass of flaggy grits with *Lingulella davisi* and *Cruziana semiplicata*, which clearly correspond with the Ffestiniog series. Above is a small thickness of unfossiliferous slates overlaid directly by the basal grit of the Ordovician.

The Bronllwyd grit evidently represents either the whole or a part of the grits of the Harlech area; and probably the Llanberis slates correspond in part with the more slaty beds below the Harlech grits. But as the base of the series is not visible in Merionethshire, it is not certain whether the grits begin at exactly the same horizon.

South Wales

The Precambrian mass of St. David's is completely surrounded by Cambrian beds except where it runs out to sea. Another Cambrian area stretches eastward from the N.E. corner of St. Bride's Bay. Here all the divisions are thinner and the succession is incomplete, as set out in the table on page 320. The lowest division, the Caerfai series, has a conspicuous basal conglomerate and consists mainly of green sandstones below and red shales above, without recognisable zone-fossils. The Solva series follows with a slight discordance: it consists mainly of sandstones with a good many fossils of the *Paradoxides* fauna. The Menevian is composed of shales and mudstones, also with several species of *Paradoxides* and a fairly rich fauna. The succession is closed by about 2,000 feet of flaggy shales and sandstones, representing only the lower part of the Lingula Flags of North Wales.

Welsh Borders and Midlands

Throughout this region there are several small outcrops of Cambrian rocks and they have been found in bores over a wide area. The lower beds were originally sandy and now form a conspicuous quartzite, with here and there small lenticles of fossiliferous limestone near the top. The upper half of the succession is shaly and represents more or less of

the Lingula Flags and Tremadoc. Except in Warwickshire the succession is nowhere complete.

The most interesting area is in the Wrekin-Caradoc district in Shropshire, as here numerous trilobites of the *Olenellus* and *Paradoxides* faunas have been found. The subdivisions locally adopted are as follows:

Upper Cambrian	Shineton Shale. *Orusia* or Black Shale.
Middle Cambrian	Upper Comley Sandstone.
Lower Cambrian	Lower Comley Sandstone. Wrekin Quartzite.

The Wrekin Quartzite is a white rock with grains of green glauconite: it is unfossiliferous and rests unconformably on the Uriconian lavas and on the Rushton Schists. The Lower Comley Series is mainly sandstone coloured green by a high proportion of glauconite. Above this comes about 6 feet of a pinkish sandy limestone containing *Callavia* (a sub-genus of *Olenellus*) *Eodiscus* and *Protolenus*. The last-named is a genus intermediate in range between *Olenellus* and *Paradoxides,* well known in America, but not found elsewhere in Britain. At the top of this is a slight discordance marked by a conglomerate. The Middle Cambrian or Upper Comley Sandstone, which includes some shales, contains *Eodiscus* and several species of *Paradoxides*. There is another break above this and the next division consists of dark shale with the trilobite *Parabolina spinulosa* and the brachiopod *Orusia*: it is therefore of Upper Lingula Flag (Dolgelly) age, while the higher division, the Shineton Shale, contains *Dictyonema,* characteristic of the lower part of the Tremadoc (see table on p. 320).

In the Malvern range the succession is generally similar: although *Olenellus* has not been found there can be little doubt that its zone is represented. At the base is the Malvern Quartzite, followed by the Hollybush Sandstone, which corresponds to part of the Comley Sandstone, but does not range so high, including only the lower part of the Menevian. After a considerable gap, the next succeeding division, the White-leaved Oak or Black Shale is equivalent to the Lower Lingula (Maentwrog), while the Bronsil or Grey Shales are of Tremadoc age. There are thus two considerable gaps in the succession.

Near Nuneaton in Warwickshire the succession is probably complete. At the base, resting on the Precambrian Caldecote volcanics, is the Hartshill Quartzite, a pinkish rock extensively quarried for road-metal. Near the top is a band of pink limestone, very like the Comley Limestone, with *Hyolithus* and *Coleoloides,* primitive mollusca rather like pteropods; just above this at the base of the next series is a nodular band with *Callavia*. This next series comprises a considerable thickness of black shale, locally subdivided into three series but conveniently

known as a whole as the Stockingford Shales. *Dictyonema* occurs some way below the top. Numerous igneous intrusions in this series are of considerably later date.

Black shales of Stockingford types have been found in bores near Leicester along the continuation of the Charnwood axial line, and shales of Tremadoc age in similar circumstances at Calvert in Buckinghamshire, as part of the London Palaeozoic plateau.

Lake District

The oldest dated rocks of the Lake District are the Skiddaw Slates, mainly Ordovician, but in part Cambrian. How much of the series is Cambrian, and how much of the Cambrian is represented, is unknown, owing to folding and cleavage, but Tremadoc graptolites, such as *Bryograptus* and *Clonograptus*, have been found at Barf, near Keswick, though apparently only in screes.

The Manx Slates of the Isle of Man may possibly include some Cambrian beds, though no fossils of diagnostic value have been found. They lie on the continuation of the trend-lines of the Skiddaw Slates.

Scotland

Cambrian beds occupy a narrow strip of country extending from Loch Eireboll to Skye, between the Precambrian rocks of the western coast on the one side and the overthrust schists of the Highlands upon the other. They lie unconformably upon both the Torridon sandstone and the Lewisian gneiss, and the surface upon which they rest had been worn down to a plane before they were deposited (Fig. 107). They are themselves in many places involved in the overthrust zones and are sometimes inverted. It is perhaps of interest to note that the steeply inclined present position of the base of the Cambrian, once a sea-floor, shows that the horizontality of the Torridonian is a pure accident. It must once have been tilted and then tilted back again.

The base is generally a fine conglomerate or pebbly grit. The lower part of the system is arenaceous, while the upper part consists almost entirely of dolomitic limestones (the Durness Limestone). Lithologically three main divisions are recognised:

3. Calcareous Series .	Limestones, generally dolomitic, with bands of chert. (Durness Limestone.)
2. Middle Series, partly arenaceous, partly calcareous.	Quartzites and grits with *Salterella*. (Serpulite grit.) Dolomitic shales, mudstones and limestones, with horizontal worm-casts. (Fucoid beds.)
1. Arenaceous Series .	Flaggy grits and quartzites (finer grained towards the top, with vertical worm-casts and burrows, forming the 'Pipe-rock').

As a whole the deposits clearly indicate a gradual deepening of the sea with minor oscillations or variations in the rate of subsidence. But

the depth attained was never great, for even the dolomitic rocks of the upper division are often full of worm-casts.

The **Arenaceous Series** is without fossils excepting the worm-casts and burrows of the Pipe-rock.

In the **Middle Series** *Salterella* and worm-casts are the commonest fossils. But several species of *Olenellus* have been found in the Fucoid beds, and along with them are other forms characteristic of the *Olenellus* series, such as *Kutorgina*, *Hyolithes*, etc. A single specimen of *Olenellus* is also recorded from the Serpulite grit. The whole of the Middle series and of the underlying Arenaceous series must therefore belong to the *Olenellus* or lower division of the Cambrian system.

The first thirty feet of the Durness Limestone is also referred to the same division, on account of the presence of *Salterella rugosa* and *S. pulchella* (which occur in the *Olenellus* beds of North America). But the main mass of the **Durness Limestone** contains a different and very remarkable fauna, entirely unlike any other known in Britain.

Gastropods are the dominant group, chief amongst them being the genera *Maclurea* and *Ophileta*. Lamellibranchs (*Euchasma*), brachiopods, sponges and a few trilobites are also found. None of the species are known in any other British area, but most of those which have been identified occur in Canada and Newfoundland in the Beekmantown Limestone, a formation which some American geologists regard as Ordovician, while others consider it to include some of the Upper Cambrian. In Scotland no forms definitely assignable to the Middle Cambrian of the Welsh Borderland have been found, and there may be a hiatus in the middle. It seems clear that the uppermost two

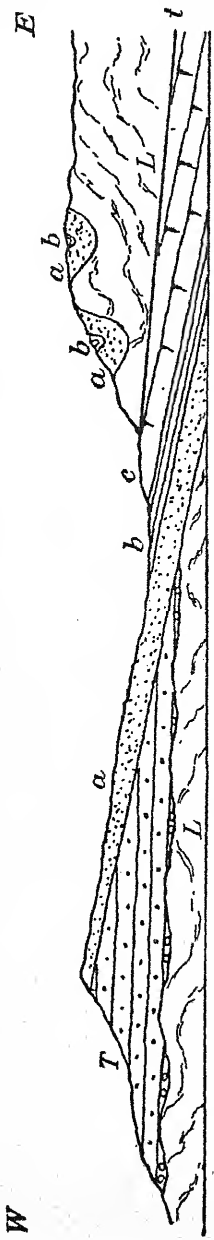


FIG. 107.—DIAGRAMMATIC SECTION ACROSS THE NORTH-WEST HIGHLANDS.

L, Lewisian gneiss; *T*, Torridon sandstone; *a*, Arenaceous series of Cambrian; *b*, Middle series; *c*, Calcareous series; *t*, Thrust-plane.

Note.—The overthrusting is much more complex than is shown in this diagram.

Faunas.	North Wales.		South Wales.	Shropshire.	Malvern.	Nuneaton.	Scotland.
Shumardia.	Tremadoc Series			Shineton Shales	Bronsil Shales	Stockingford Shales.	Durness Limestone
Olenus.	Lingula Flags.	Dolgelly Group		Orusia Shales			
		Ffestiniog Group					
		Maentwrog Group	Maentwrog Group		White-leaved Oak Shales		
Paradoxides.	Menevian Series			Upper Comley Sandstone			
	Upper Harlech Series		Solva Series		Hollybush Sandstone		
Olenellus.	Lower Harlech Series		Caerfai Series	Lower Comley Sandstone		Hyolithus Limestone	Quartzite Series
				Wrekin Quartzite	Malvern Quartzite	Hartshill Quartzite	

Correlation Table of the Cambrian System of Great Britain. The vertical columns do not represent thicknesses of strata: an equal space is assigned to each of the four faunas.

or three hundred feet of the Durness Limestone are Ordovician, and that the whole of it was laid down in a basin entirely separate from the rest of the British Cambrian, in a clear sea free from muddy sediment, with an entirely different fauna. Much of the limestone has been converted to dolomite, and some beds are silicified to chert.

Ireland

Rocks which have usually been supposed to belong to the Cambrian system occur at Bray Head and other localities in the counties of Dublin, Wicklow and Wexford; but the only fossils found are worm tracks and burrows and the peculiar markings known as *Oldhamia*, whose organic nature has been doubted. No fossils certainly referable to the Cambrian have been found anywhere in Ireland.

CHAPTER XVII

THE ORDOVICIAN SYSTEM

At the end of the Cambrian period there was nearly everywhere within the Palaeozoic geosyncline a phase of slight uplift and gentle folding, of rather more importance than the disturbances recorded by mere gaps in the Cambrian succession as recorded in the last chapter. Hence, especially in the type area in North Wales, the Ordovician rocks rest discordantly on the eroded edges of different members of the older rock-series. Another eventual effect was a wider extension of the sea, so that Ordovician rocks now cover a considerable area. They are found in Cornwall; in South Wales; in North Wales and Shropshire; in the Lake District and the Pennine Chain; in the Southern Uplands of Scotland; and in several areas in Ireland.

Three different facies, or types of deposit, may be recognised, viz. the shelly, the graptolitic and the volcanic. In the shelly facies the deposits are more or less sandy and calcareous and generally light in colour, forming now a series of rough and sometimes rather gritty slates, with beds of sandstone, and occasional bands of nodular limestone. Brachiopods and trilobites are the predominant fossils, with corals and cystideans in the calcareous bands, and gastropods and lamellibranchs in the more sandy beds.

In the graptolitic facies the deposits are thinner, and the sediment is finer, forming dark slates or shales, often with bands of chert. Graptolites are the common fossils, with radiolarians in the cherts; but in some of the beds trilobites are abundant. The trilobites, however, usually possess certain peculiar characteristics. They are either blind (e.g. *Trinucleus*, *Ampyx*), or with eyes of extraordinary size (e.g. *Aeglina*); and it has been suggested that they lived at such a depth that normal eyes were useless.

In the third or volcanic facies, the rocks consist chiefly of lava-flows, ashes, tuffs and agglomerates. In the fragmental beds fossils are sometimes found, occasionally in abundance. The volcanic rocks may be interstratified with deposits of either the shelly or the graptolitic facies, and were no doubt deposited upon the ocean-floor.

These three facies do not represent distinct periods. They characterise different areas rather than different epochs, and owe their characters to the conditions under which they were laid down. The shelly facies was the normal type of deposit in moderately shallow water, into which a considerable supply of sediment was brought by

rivers from the neighbouring land. The graptolitic facies was formed much more slowly, and was evidently laid down at a greater distance from the shore, reached only by the finest of the material derived from the land. The volcanic facies was not confined to any particular depth, but in the British area all the volcanic rocks of this period appear to have been submarine. Marine deposits are often interstratified with them, but never deposits formed upon the land.

As in the case of the Cambrian beds, the thickness of the system varies greatly. In North Wales, where the volcanic and shelly facies are well developed, a thickness of 10,000 feet or more has been assigned to the Ordovician system. In the Moffat area, in the south of Scotland, where the graptolitic facies prevails, the base is not seen, but about 120 feet probably represents the upper six or eight thousand feet of the Welsh estimate.

Fauna.—The fauna is much richer in species, and generally in individuals, than that of the Cambrian system. As already remarked, its character varies with the nature of the sediments; but on the whole brachiopods, trilobites, polyzoa and graptolites are the dominant groups.

Of the brachiopods, the genus *Orthis* is the most abundant, both in species and in individuals; but *Plectambonites*, *Strophomena* and *Leptaena* are also common. Amongst the trilobites *Agnostus* survives from the Cambrian period; *Trinucleus* is confined to this system and ranges from base to summit. *Ampyx*, *Asaphus* and *Ogygia* are particularly characteristic of the lower divisions; *Phacops*, *Calymene*, *Homalonotus*, *Illaenus*, and *Cybele* of the higher beds; while the remarkable genus *Staurocephalus* occurs especially at one well-defined horizon near the top.

By far the greater number of the genera of graptolites belong to this system, and the Ordovician genera usually conform to one of two types of structure. Either they are branched and each branch is uniserial (e.g. *Tetragraptus*, *Didymograptus*), or they are unbranched and the single stem is biserial (e.g. *Climacograptus*, *Diplograptus*). Simple uniserial forms are rare (*Azygograptus*), and even these differ markedly from the characteristic Silurian genus *Monograptus*. The remarkable form *Phyllograptus* is quadriserial.

Corals are common in the calcareous bands, *Halysites* and *Heliolites* being the genera most often found. Cystideans are abundant in the upper beds, when these belong to the shelly facies. *Echinosphaerites*, *Caryocystites* and *Hemicosmites* are the most important genera. Polyzoa are sometimes very abundant. *Monticulipora* is the most widespread genus, while *Ptilodictya* and *Phyllopora* are common in the upper beds. Gastropods and lamellibranchs are found chiefly in the sandy deposits, where they sometimes occur in great abundance. *Bellerophon*, *Murchisonia* and *Raphistoma* among the gastropods, and *Ctenodonta* and *Modiolopsis* among the lamellibranchs are perhaps the most important.

The cephalopods are represented chiefly by the genus *Orthoceras*, but they are not often found in any great numbers.

There has been considerable difference of opinion as to the best method of subdividing the Ordovician system. By various authors it has been cut up into three, four, or five series. The scheme here adopted is that given in recent publications of the Geological Survey, and is in essentials a compromise. The following table shows the classification according to graptolite zones, with in the third column a list of some of the characteristic trilobites of each series: these last are not in strict stratigraphical order; i.e. they are not zones, but generalised groups. Many authorities group the Caradoc and Ashgill together as the Bala series, while others divide the Llanvirn between the Arenig and Llandeilo series. The name Ashgill is derived from the Lake District, while the others come from North and South Wales and the Welsh Borderland.

	Series.	Graptolite Zones.	Characteristic Trilobites.
Bala Series.	Ashgill Group.	*Dicellograptus anceps* *Dicellograptus complanatu*	*Trinucleus seticornis.* *Cybele verrucosa.* *Cheirurus juvenis.*
	Caradoc Group.	*Pleurograptus linearis* *Dicranograptus clingani* *Climacograptus wilsoni* *Climacograptus peltifer* *Nemagraptus gracilis*	*Trinucleus concentricus.* *Phacops apiculatus* *Asaphus powisi.*
	Llandeilo Series.	*Glyptograptus teretiusculus*	*Trinucleus favus.* *Asaphus tyrannus.* *Ogygia buchi.*
	Llanvirn Series.	*Didymograptus murchisoni* *Didymograptus bifidus*	*Trinucleus gibbsi.* *Placoparia,* species. *Aeglina binodosa.* *Ogygia selwyni.*
	Arenig Series.	*Didymograptus hirundo* *Didymograptus extensus* *Dichograptus* species	

Note: the zone of *Nemagraptus gracilis* was formerly placed by most writers in the Llandeilian: the practice of the Geological Survey is now as given above.

South Wales

In most of the Ordovician areas the succession is complicated by the presence of volcanic rocks, which interrupt the regular sequence of fossiliferous deposits. In South Wales, however, the amount of volcanic material is comparatively small; and it will accordingly be convenient to begin with the description of this region.

The Ordovician rocks form a broad band extending eastwards from St. Bride's Bay to Llandeilo; and they occur also further to the north in the neighbourhood of Builth and elsewhere.

The Arenig series consists, from below upwards, of grits, sandstones, mudstones and shales, in that order, thus indicating a gradual deepening of the water. Some dendroid graptolites are found in the lower beds,

followed by those of the *Didymograptus extensus* group. Some characteristic trilobites are *Ogygia selwyni* and *Calymene tristani*, with *Orthis*, *Orthoceras* and the earliest starfish. In Pembrokeshire and especially on Skomer Island is a considerable development of lavas and ashes.

The **Llanvirn Series** consists mainly of black shales, with some tuffs and lavas; the thickness varies considerably with a maximum of 2,000 feet. The series is characterised specially by the 'tuning-fork' graptolites, *Didymograptus bifidus*, *murchisoni* and other species which are specially well seen at Abereiddy Bay. Some important trilobites are species of *Placoparia* and *Trinucleus.*

The **Llandeilo Series,** or **Llandeilian,** consists in part of sandstones and calcareous flags, in part of black shales or slates, and in part of volcanic lavas and tuffs. The sandstones and calcareous flags usually attain their greatest development in the middle of the series, and wherever they occur trilobites become the common fossils, especially *Asaphus tyrannus*, *Ogygia buchi* and *Trinucleus favus.* The volcanic rocks are interstratified with the lower slates and are thickest towards the west, in the neighbourhood of Abereiddy Bay.

The shaly beds of the Llandeilian are continued upwards into the **Caradocian,** with no lithological change. Locally the shales, whether belonging to the Llandeilian or the Caradocian, are known as the *Dicranograptus* shales, on account of the abundance, in places, of the genus *Dicranograptus.* Occasional sandy and gritty beds occur at various horizons, and these contain brachiopods and trilobites. At the top the calcareous matter increases in amount and sometimes forms a definite band of black limestone, which is seen at Robeston Wathen and elsewhere. It contains corals, such as *Halysites* and *Heliolites*, brachiopods, trilobites, etc. It is, however, probable that some of the outcrops which have been referred to the Robeston Wathen limestone belong to the succeeding series.

The **Ashgillian Series** consists of a yellowish sandy limestone at the base, followed by a succession of blue-grey and greenish shales with occasional calcareous bands. The whole series belongs to the shelly facies, and is especially characterised by the abundance of cystideans (*Caryocystites*, etc.) and of trilobites (*Trinucleus seticornis*, etc.). The basal limestone, known as the Sholeshook limestone, contains in addition the trilobites *Staurocephalus globiceps* and *Phillipsinella parabola.*

There is probably an unconformity between the Caradocian and Ashgillian series. Not only is there a great and sudden change in the fauna and the character of the deposits, but it appears that the Sholeshook limestone does not always rest upon the same horizon of the *Dicranograptus* shales.

In Wales the Caradocian and Ashgillian are commonly grouped together as the Bala series.

North Wales

In North Wales the Ordovician rocks occupy the Snowdon synclinal and form a broad belt around the landward side of the Harlech dome. They spread northwards into Anglesey, while towards the east they dip beneath the Silurian beds, but rise again to the surface in the Berwyn and the Breidden Hills. In general they lie with a slight unconformity upon the Cambrian beds, but in Anglesey they have overlapped the Cambrian system altogether and rest directly upon the Mona complex with a basal conglomerate 3,000 feet thick.

There was great volcanic activity in the period, with a gradual shift to the north and east of the centres of eruption. The earliest was in Rhobell Fawr at the very base of the Arenig, continuing in that area to the top of the Llandeilo, whereas in the Snowdon district activity did not begin till the base of the Llandeilo and reached a maximum in the Caradocian: there was no vulcanicity in the Upper Bala (Ashgillian). Accordingly, in the Snowdon area and around the Harlech dome, the system consists very largely of volcanic rocks, while in the Berwyn and the Breidden Hills the deposits are chiefly normal marine sediments with only occasional bands of ash. Owing to the general absence of fossils in the volcanic rocks it is often difficult to determine their age with precision, and the difficulty is increased by the irregular and spasmodic nature of the outbursts.

The system begins with an inconstant basal grit, the Garth Grit, which rests unconformably upon the Cambrian. This is followed by a series of slates and flaggy beds, sometimes calcareous or mixed with volcanic ash: in these *Didymograptus extensus* occurs. In the succeeding calcareous and ashy bands trilobites such as *Ogygia selwyni* and *Calymene parvifrons* are met with. These beds together form the **Arenig** Series.

The next series, the **Llanvirn,** consists mainly of mudstones and shales with a graptolitic fauna, specially characterised by the 'tuning-fork' Didymograptids. In the Cader Idris district however, and northwards, one of the greatest volcanic episodes in Britain began at this time, the lavas and ashes in the Arenig district being some 4,000 feet thick. In the Snowdon syncline the series is mainly slates, nearly 2,000 feet thick, which are extensively worked at Blaenau Ffestiniog.

The same type of sedimentation continued up into the **Llandeilo** Series, as also in some areas did the volcanic activity, especially in the Arenig and Cader Idris districts. Further east, in the Berwyn dome, the beds were laid down in rather shallower water, and the Llandeilo Limestone makes its appearance, with trilobites such as *Ogygia buchi* and *Asaphus tyrannus*, as in South Wales: there are also some unimportant bands of ash and a few lavas.

The **Bala Series** in the wide sense, including the Caradocian and

Ashgillian, is most extensively developed in the Snowdon region, where it includes a great thickness of volcanic rocks.

The **Caradocian** of North Wales varies greatly in its development. In the Snowdon area it consists very largely of volcanic rocks, chiefly rhyolitic lavas and agglomerates. Near Conway it is represented by *Dicranograptus* shales, similar to those of South Wales. Towards the south and east, around Bala and in the Berwyn Hills, it consists of sandstones and bluish slates with two or three beds of volcanic ash and an occasional band of limestone often called collectively the Bala Limestone. Brachiopods, trilobites, etc., are here the common fossils, but there are intercalations of black slate with imperfectly preserved graptolites. Amongst the more abundant fossils may be mentioned *Tetradella complicata*, *Phacops apiculatus*, *Trinucleus concentricus*, *Orthis elegantula*, *Murchisonia gyrogonia*, *Ctenodonta varicosa*.

On the whole, therefore, in the east the Caradocian belongs chiefly to the shelly facies; towards the west it becomes graptolitic and volcanic.

Wherever the **Ashgillian Series** is known in North Wales, it is of the shelly type and closely resembles the corresponding beds of South Wales. The deposits are blue-grey slates, often calcareous and sometimes with definite bands of limestone. No volcanic rocks are known. A limestone with *Staurocephalus* occurs at Rhiwlas near Bala, and is evidently the equivalent of the Sholeshook Limestone of South Wales. Slaty beds with the typical Ashgillian fauna are found in general beneath the Silurian, but owing to the unconformity of the latter, the higher beds of the series are often absent.

In North Wales, as in South Wales, there is a decided break in the succession between the Caradocian and Ashgillian series. This is sometimes due in part to faulting, but the fact that such a break occurs at the same horizon in both areas suggests that the two series must be unconformable.

Shropshire

In Shropshire Ordovician strata are found on both sides of the Longmynd, but with a considerable difference in their development. On the west the valley occupied by the Shineton Shale is bounded by the great craggy escarpment of the Stiperstones Quartzite, the basal division of the **Arenig Series**, and the succession is complete to the top of the Caradocian, covering a large area stretching into Wales. The type of sediment is much the same as in North Wales and some volcanic rocks are included. The Mytton Flags, which succeed the Stiperstones Quartzite contain many veins with lead and zinc ores, barytes and calcite: in the Shelve district these have been worked since Roman times. The succeeding Hope Shales, with tuning-fork graptolites do not carry any mineral veins: they represent the **Llanvirn**. Above

these come the Stapeley volcanics and the rest of the system consists of an uninteresting set of shales and flags with the usual fossils and some volcanics, to which a multitude of local names have been applied. There are many intrusions, the most important being the dolerite laccolith of Corndon.

On the eastern side of the Longmynd the lower divisions are absent and the Ordovician begins and ends with the **Caradocian,** the Caradoc Sandstone in its original type locality. This consists largely of highly fossiliferous sandy flags and shales in which many of the zone graptolites have been found, as well as trilobites and other fossils characteristic of the shallow water facies. There are no igneous rocks.

The Precambrian mass of the Uriconian and Longmyndian rocks formed a land area during the earlier part of the Ordovician period, and even the Caradocian submergence did not last very long, as there are no representatives of the Ashgillian in Shropshire.

It is evident that both in Ordovician and Silurian times some tectonic feature or barrier along the line of the present great Stretton fault was a dominating factor in the geography of the period, as a forerunner of the Caledonian earth movements of the Old Red Sandstone.

There are no Ordovician rocks in the Malvern Hills, or in any of the Midland areas where Cambrian rocks exist.

Northern England

The greater part of the Lake District north of a line drawn from the head of the Duddon estuary to the upper end of Windermere and thence to the granitic intrusion of Shap Fells, is formed of Ordovician rocks. Ordovician rocks are also exposed as small inliers at the foot of the Pennine Chain near Cross Fell, and near Sedbergh and Settle in Yorkshire.

The oldest rocks of the Lake District (Fig. 108) are known as the **Skiddaw Slates.** The base of the series is not seen and the thickness is unknown, owing to intense folding, but it probably amounts to several thousand feet. The oldest known graptolites are of Tremadoc type, followed by Arenig zones and at least the lower part of the Llanvirn, with *Didymograptus bifidus*. The series consists mainly of dark shales or slates, with some flaggy and gritty beds and a coarse grit near the top. There is widespread cleavage, but the slates are not of good quality. The spotted slates and chiastolite-slates around the Skiddaw granite, of Caledonian age, afford a classical example of low-grade thermal metamorphism (see page 268).

It is possible that the Manx Slates of the Isle of Man are of the same age, but no definite zone-fossils have been found in them. They show some fine examples of crush-conglomerates (see page 271).

The Skiddaw slates are followed by an enormous mass of basic,

andesitic and rhyolitic lavas, ashes, and agglomerates often called the **Borrowdale Series**. The real thickness is unknown, but must amount to many thousands of feet. In the Cross Fell inlier dark slates with *Didymograptus murchisoni* are interstratified with the lower agglomerates, and there can be little doubt that the volcanic series belongs mainly to the Llandeilian. But the eruptions continued into the succeeding period. Moreover, it is quite possible that older rocks have been included in the series.

The **Caradocian** is represented by calcareous and ashy shales and limestones, with beds of volcanic ash and a band of rhyolitic lava, locally known as the **Sleddale Group**. The total thickness is very much less than in North Wales, and the proportion of limestone is greater; but as in the Berwyn Hills, the fossils are mostly brachiopods and trilobites.

The **Ashgill Group** begins with a limestone containing *Staurocephalus globiceps* and *Phillipsinella parabola*, evidently corresponding with the Sholeshook and Rhiwlas limestones. The highly fossiliferous limestone of Keisley appears to belong to this band. Above the limestone is a series of blue and grey shales, which are well exposed at Ashgill, near Coniston.

The Sleddale group and the Ashgill group together have long been known as the Coniston Limestone series, and are equivalent to the Bala of Wales.

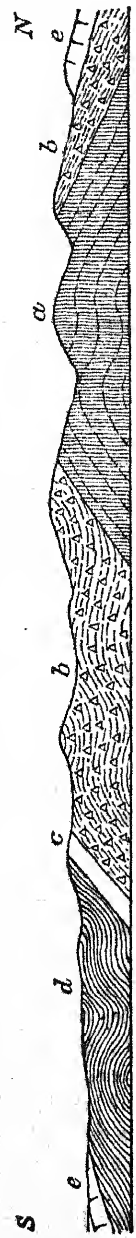


FIG. 108.—DIAGRAMMATIC SECTION ACROSS THE LAKE DISTRICT.

a, Skiddaw Slates; *b*, Borrowdale series; *c*, Coniston Limestone series; *d*, Silurian; *e*, Carboniferous Limestone.

SOUTHERN UPLANDS OF SCOTLAND

The Southern Uplands are formed almost entirely of Ordovician and Silurian rocks, which stretch across the country from sea to sea. Geologically they may be divided into three parallel belts with a south-westerly trend. In the Northern Belt Ordovician rocks predominate. The Central Belt is formed chiefly of the lower beds of the Silurian system; but Ordovician beds are exposed in the cores of the anticlines. The Southern Belt consists of Silurian rocks belonging to the Wenlock series.

Throughout the region the beds are thrown

into sharp folds which trend in the direction of the belt and which usually lean over to the south (Fig. 110, p. 341). On account of the resulting constant dip, the thickness was originally very greatly overestimated, but the interbedded graptolitic bands show that this apparent thickness is due to repetition by a series of isoclinal folds.

In the Central Belt the Ordovician deposits belong to the graptolitic facies, with volcanic rocks interstratified at certain horizons. But towards the north and west the fine black graptolite-bearing shales are gradually replaced by coarser sediments. In the lower part of the system the fine material extends even to Girvan and Ballantrae, but higher up the coarser sediments spread further and further to the south. Generally, in the Central Belt the graptolitic deposits predominate, in the Northern Belt the coarser material begins to prevail. The special characteristics of the Northern Belt attain their maximum development in the neighbourhood of Girvan and Ballantrae, in Ayrshire.

Everywhere the **Arenig Series** consists chiefly of basic and andesitic lavas with thin bands of chert and mudstones. These are followed by radiolarian cherts, mudstones and grey shales with bands of tuff. The greatest development of the volcanic rocks is found near Girvan and Ballantrae.

In the Moffat district in the Central Belt the lowest visible rocks consist of radiolarian cherts and mudstones followed by black shales and grey ashy mudstones. The shaly beds are known as the Glenkiln Shales: the lowest graptolite zone present is that of *Nemagraptus gracilis*, hence the Glenkiln Shales are of Lower Caradocian age, the Llanvirn and Llandeilo divisions not being represented. Their total thickness in the Central Belt is only about 20 feet. On certain bedding planes graptolites are extraordinarily abundant, indicating slow deposition in deep water.

Towards Girvan on the coast of Ayrshire the Glenkiln Shales are replaced by conglomerates, sandstones, flags and limestones known as the Barr Series, with brachiopods, trilobites, corals, etc., a very rich fauna of the shelly facies, but occasional shaly bands with graptolites permit of correlation with the Moffat area. The total thickness is about 800 feet.

The Glenkiln Shales are followed without interruption by the Hartfell Shales of very similar character below, but less shaly towards the top, with fewer fossils. The total thickness is about 100 feet. The five graptolite zones of the upper Caradocian and Ashgillian have been identified here, so that the Glenkiln and Hartfell series together correspond to the Bala Series of Wales though not equivalent to Caradocian and Ashgillian, each to each, as the dividing line is drawn at different zones.

In the Girvan district the equivalent of the Hartfell Shales, there called the Ardmillan series, has thickened to 2,800 feet. Numerous

local names are applied to the lithological subdivisions, which consist of a great variety of sandstones, flags, mudstones and shales with occasional graptolites, and a good many trilobites, etc., in the coarser sediments.

Ireland

In Ireland the large mass of ancient rock which extends from Dublin Bay to Waterford and Carnsore Point is formed chiefly of Ordovician rocks, though some of the oldest beds are believed to be of Cambrian or even Precambrian age. Ordovician rocks also occupy a narrow belt extending from Belfast Lough west-south-westward into the southern part of County Leitrim. This is evidently the direct continuation of the Ordovician belt of the Southern Uplands of Scotland. Besides these two principal areas there are several smaller outcrops.

In general the deposits resemble those along the same strike in Great Britain.

Near Waterford, Llandeilo slates and limestone are followed by *Dicranograptus* shales similar to those of South Wales. Farther north, at Portraine and Kildare, a series of lava-flows, andesitic ash and shales with Caradocian fossils is succeeded by limestones with Ashgillian forms —the succession here being similar to that of North Wales and the Lake District. Towards the west, in Galway and Mayo, a remarkable feature is a calcareous development in the Arenig series containing trilobites similar to those of Sweden and Russia.

In the northern belt the lower beds appear to consist largely of graptolitic shales and radiolarian cherts as in the south of Scotland; but the shelly facies of the Ashgillian series is well developed at Pomeroy, in Tyrone, where it consists of calcareous sandstones, flags, and grits, with graptolitic shales towards the top.

Cornwall

In the extreme south of England, around Veryan Bay, in Cornwall, there is a small Ordovician area. Lithologically and palaeontologically it belongs to the French development of the system rather than to the Welsh or English type. It consists chiefly of slates and quartzites, with some volcanic beds and bands of limestone and radiolarian chert. But the folding and faulting is so intense that it is difficult to make out the succession. The quartzite of Perhaver Beach contains *Calymene tristani*, *Cheirurus sedgwicki*, etc., and appears to correspond closely with the Grès de May of Normandy, which is approximately on the same horizon as our Llandeilo series.

<table>
<tr><th>Wales.</th><th colspan="2">Lake District.</th><th>Moffat.</th><th>Girvan.</th><th>Zones.</th></tr>
<tr><td rowspan="7">Bala Series</td><td rowspan="2">Ashgill Group</td><td rowspan="7">Coniston Limestone Series</td><td rowspan="5">Hartfell Shales</td><td rowspan="5">Ardmillan Series</td><td>anceps</td></tr>
<tr><td>complanatus</td></tr>
<tr><td rowspan="5">Sleddale Group</td><td>linearis</td></tr>
<tr><td>clingani</td></tr>
<tr><td>wilsoni</td></tr>
<tr><td rowspan="2">Glenkiln Shales</td><td rowspan="2">Barr Series</td><td>peltifer</td></tr>
<tr><td>gracilis</td></tr>
<tr><td>Llandeilo Series</td><td colspan="2">Borrowdale Series</td><td rowspan="3">—</td><td rowspan="3">—</td><td>teretiusculus</td></tr>
<tr><td rowspan="2">Llanvirn Series</td><td colspan="2" rowspan="5">Skiddaw Slates</td><td>murchisoni</td></tr>
<tr><td>bifidus</td></tr>
<tr><td rowspan="3">Arenig Series</td><td colspan="2" rowspan="3">Ballantrae Volcanic Series</td><td>hirundo</td></tr>
<tr><td>extensus</td></tr>
<tr><td>Dichograptus</td></tr>
</table>

Table to show the relation of the northern Ordovician rocks to the type area in Wales. In this table an equal space is assigned to each graptolite zone: hence the height of each division of the columns bears no relation to the actual thickness of the rocks, only to the number of zones included.

CHAPTER XVIII

THE SILURIAN SYSTEM

There are now very few general small-scale maps in which the mutual boundaries of the Ordovician and Silurian systems are correctly shown. Recent research has indicated that, especially in Central Wales, Silurian rocks cover a good deal more ground and Ordovician rocks a good deal less than is shown in most, even recent, maps of a general character. Moreover in Scotland the boundaries are so intricate, owing to folding, that the two systems can only be shown in a generalised fashion. It is only in the Lake District that it is possible to draw a definite simple line. From the above it will be apparent that the main outcrops of the Silurian lie in much the same areas as the Ordovician, but there are more small inliers in several districts and some of these are of considerable interest.

Geographically the principal outcrops may be grouped as follows:

(1) *Wales and the Welsh Borders.*—In Wales the Silurian beds form a broad band concentric with the Harlech dome, stretching from the mouths of the Conway and the Dee on the north coast to the estuaries of the Dyfi and the Teifi on the shores of Cardigan Bay. But the simplicity of the structure is destroyed by the violent folding to which the area has been subjected, with the result that the Ordovician rocks rise to the surface in many places and interrupt the continuity of the band. Similar folding also brings up the Silurian from beneath the newer beds farther to the east, in the counties bordering upon Wales and even in the southern part of Staffordshire.

(2) Silurian beds form practically the whole of the southern portion of the Lake District, excepting where they are covered by later deposits, and of the large and little-known tract of the Howgill Fells to the south-east, as far as Sedbergh in Yorkshire. There is also an area of mainly Silurian rocks, with some Ordovicians, in Ribblesdale, just north of the Craven faults.

(3) *South of Scotland.*—The Silurian rocks occur principally in a broad belt which forms the southern part of the Southern Uplands, stretching from the Mull of Galloway to St. Abb's Head. But Silurian beds are also occasionally exposed in the Midland Valley of Scotland, especially in Lanarkshire.

(4) *Ireland.*—A broad triangular area, with its base extending from Belfast Lough to Clogher Head and Balbriggan, and its apex near the Shannon, is evidently the continuation of the belt of the Southern

Uplands. Westward the belt disappears beneath the Carboniferous Limestone; but there are smaller outcrops in the western part of Connaught, and several large inliers in Munster.

Except in the south, in County Kerry, Pembrokeshire, Gloucestershire, and in the Mendip Hills, no volcanic rocks are known in the Silurian system of the British Isles. But in the sedimentary deposits both a shelly and a graptolitic facies may be recognised. In the shelly facies the deposits are more or less sandy or calcareous, the limestones being of greater thickness and importance than in the Ordovician system. The fossils are chiefly brachiopods, trilobites, corals and crinoids. In the graptolitic facies, where it is typically developed, the sediment is finer and forms black shales, as amongst the Ordovician rocks. Thin-shelled species of *Orthoceras*, as well as graptolites, are abundant in some of these beds.

But, excepting in the lower part of the system, the distinction between the two facies is less marked than in the Ordovician system. Graptolites are common in some of the shales which are neither black nor fine in texture, and they often occur together with brachiopods and other fossils characteristic of the shelly deposits.

Fauna.—In its general characters the fauna is similar to that of the Ordovician system, although many of the genera and most of the species are distinct. Crinoids, however, take the place to a large extent of the Cystideans, and Cephalopods are considerably more abundant than in the older beds. Towards the top of the system the earliest known remains of fishes occur. The graptolites are mostly uniserial and belong chiefly to the family Monograptidae, *Monograptus*, *Cyrtograptus* and *Rastrites* being the most characteristic genera. But some of the Ordovician genera, such as *Diplograptus* and *Climacograptus*, range into the lowest or Llandovery series; and the peculiar biserial genus *Retiolites* occurs at a somewhat higher horizon. Another group of Hydrozoa, namely the Stromatoporoidea, is common in the limestones. Corals are more abundant than in the Ordovician, and often form a large part of the calcareous bands. *Favosites*, *Halysites*, *Heliolites*, *Acervularia* and *Omphyma* are amongst the common genera; with *Lindstroemia* and *Petraia* in the Llandovery. Cystideans are not so common as in the Ordovician system; but Crinoids are abundant in some of the limestones (e.g. *Crotalocrinus*). The earliest British sea-urchins (*Palaeodiscus* and *Echinocystis*) occur in the Lower Ludlow. Starfish, both Asteroidea and Ophiuroidea, are found in the Ludlow beds. Brachiopods are particularly abundant. Most of the Ordovician genera continue into this period, and in addition *Pentamerus*, *Stricklandia*, *Dayia* and other genera appear. Trilobites are also common. *Calymene*, *Phacops*, *Homalonotus*, *Illaenus* and *Encrinurus* are the genera most often met with. The Phyllocarids are represented by *Ceratiocaris*, *Discinocaris* and one or two other forms. Another group

of arthropods, the Eurypterida, becomes of importance in the upper beds, the principal genera being *Eurypterus*, *Pterygotus* and *Slimonia*. The earliest scorpion occurs in the Upper Silurian. Of the Mollusca, the Gastropods and Lamellibranchs are probably about as abundant as in the Ordovician system. The Cephalopods are more numerous and they all belong to the sub-order Nautiloidea. Most of them occur in the shelly type of deposits. But thin-walled forms (e.g. *Orthoceras primaevum*) are common even in the graptolitic shales. The earliest remains of vertebrates found in the British Isles are the bones and spines of fish, which first appear in the Lower Ludlow, and become more abundant in the Bone-bed of the Upper Ludlow. They include representatives of both the Ostracoderms and the Elasmobranchs.

Classification of the Silurian System.—Although both shelly and graptolitic facies occur, yet except at the top and the bottom of the system the two are interstratified to so great an extent that there is little difficulty in correlating the larger divisions even in widely separated areas.

Only in the lowest division is there any great variation in the nature of the deposits or of the fauna. In this the shelly and the graptolitic facies are totally distinct; they usually occur in separate areas, and the change from the one facies to the other is so rapid that they are seldom found interstratified. The shelly deposits are characterised especially by the abundance of *Pentamerus*; the graptolitic deposits by *Rastrites*, *Monograptus*, *Diplograptus* and *Climacograptus*. The genus *Rastrites* is confined to this division.

The succeeding beds are generally shaly, and usually contain graptolites. In some areas limestones and sandstones also occur, but nowhere are they so greatly developed as to exclude the shales. There is, therefore, no difficulty in classifying this part of the succession according to the graptolites. Broadly, they may be divided into a lower series with *Monograptus* of the *priodon* type, and an upper series with *Monograptus* of the *colonus* type.

Finally, in all the areas where they are found, the upper beds of the Silurian system are more or less sandy; and the amount of arenaceous material increases towards the summit, where they pass upwards into the overlying Old Red Sandstone. No graptolites occur in this division. Brachiopods, etc., are found in the lower part; but the most characteristic fossils are the remarkable Eurypterids.

The zoning of the Silurian by graptolites has become so complicated, two authorities giving 26 and 29 zones respectively, that attention will be confined here to the classification by lithological divisions, and the correlations will be stated without the zonal evidence in detail, such as was given in the chapter on the Ordovician system. Moreover there are no graptolites in the highest part of the system, the family having become extinct.

The Silurian system has been classified in several different ways, but the recent tendency has been to return to the original and simple division into four series, based on the development in Shropshire and the Welsh borderland, where the system was originally described. It should be noted, however, that although several of the names of the major subdivisions are taken from this area, the development there is not really typical. It is much more calcareous than in any of the other large Silurian outcrops, where limestones are notably scarce, and grits, shales and mudstones are the characteristic sedimentary types of the system as a whole.

In the broadest general way the Silurian system may therefore be subdivided as follows:

Downton Series . .	Grey and red sandstones with eurypterids, etc.
Ludlow Series . . .	Marine sandstones and shales with *colonus* graptolites in lower part.
Wenlock Series . .	Grits and shales with *priodon* graptolites. Limestones important locally.
Llandovery Series . .	Shelly type with brachiopods and shaly type with graptolites.

Many of the graptolites in the Llandovery are survivals of Ordovician genera, but in the Wenlock and Lower Ludlow they are species of *Monograptus* and *Cyrtograptus*, simple uniserial forms.

Wales and Welsh Borders

The Silurian rocks lie upon the north-west border of a great triangular area of Old Red Sandstone which covers most of Herefordshire, Monmouthshire and Brecknockshire. They rise to the surface in the Woolhope and Usk anticlines within this area, and upon its eastern border they crop out in the Abberley, Malvern, and May Hills, and also near Tortworth. Farther east, amongst the newer beds, a few small inliers occur in the South Staffordshire coal-field.

Throughout the greater part of this region the shelly facies predominates; but graptolites are by no means rare, and towards the west the deposits gradually become more and more exclusively graptolitic.

The lowest beds are sandy or conglomeratic, occasionally calcareous, and form the Llandovery series. These are followed by a series of shales and limestones alternating with each other, the shales being sometimes graptolitic and the limestones belonging to the shelly facies. Towards the top the deposits again become sandy and Eurypterids are abundant. Finally, these sandstones gradually grow brighter in colour and pass upwards into the overlying Old Red Sandstone.

The local succession in Shropshire and Herefordshire is as follows:

Downton Series—	Red Downton Sandstone. Grey Downton Sandstone.
Ludlow Series—	Upper Ludlow Shale. Aymestry Limestone. Lower Ludlow Shale.
Wenlock Series—	Wenlock Limestone. Wenlock Shale. Woolhope Limestone.
Llandovery Series—Upper Llandovery.	

Llandovery Series.—In South Wales the whole series is present, as at the type locality at Llandovery in Caermarthenshire, but in Shropshire the lower part is missing over a large area and the higher beds rest on older rocks down to the Precambrian. At the south end of the Longmynd the ancient beaches of the period can still be traced. Here the Upper Llandovery beds are of the shelly type with *Pentamerus* and other brachiopods. It has been the custom of late to separate the highest beds of the Llandovery of central Wales as the Tarannon Shales, and even to make them into a separate series, but it seems clear that they only represent a local shaly facies of the Upper Llandovery, which does not everywhere begin at the same horizon, as shown by the graptolite zones.

Wenlock Series.—The Woolhope Limestone, Wenlock Shale and Wenlock Limestone may be looked upon as a single series, the limestones being nothing more than local developments within the shales. In the eastern outcrops the shales are bluish and belong to the shelly rather than the graptolitic facies. But towards the west they become darker in colour, and graptolites and thin-walled Orthoceratites become the predominant fossils. Several species of *Cyrtograptus*, *Monograptus priodon* and allied forms, *Retiolites*, and *Orthoceras primaevum* occur. The Woolhope Limestone lies at the base of the series and occurs chiefly in the eastern outcrops (Fig. 109). The Wenlock Limestone forms the top of the series, and is found not only in the east but also on the north-west border of the Old Red Sandstone area in Shropshire. It contains a very abundant fauna, especially corals (*Halysites*, *Heliolites*, *Favosites*

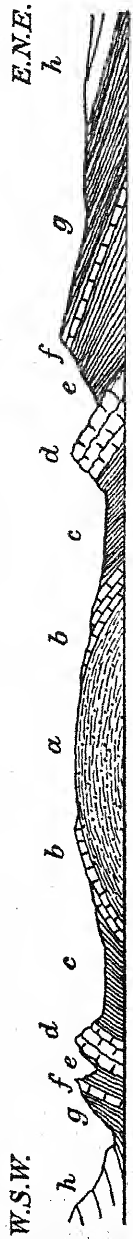


FIG. 109.—SECTION OF THE WOOLHOPE ANTICLINE. (After Murchison.)
a, Llandovery beds; *b*, Woolhope Limestone; *c*, Wenlock Shale; *d*, Wenlock Limestone; *e*, Lower Ludlow Shale; *f*, Aymestry Limestone; *g*, Upper Ludlow Shale; *h*, Old Red Sandstone.

gothlandica, *Omphyma*), crinoids (*Crotalocrinus*), trilobites (*Calymene blumenbachi*, *Phacops caudatus*, *Illaenus barriensis*), brachiopods (*Atrypa reticularis*, *Strophonella euglypha*).

Ludlow Series.—The Lower Ludlow shales are generally soft sandy shales, greyer in colour than the Wenlock shales. In the eastern part of the area they belong to the shelly rather than the graptolitic facies; but in the west, as for example near Ludlow, they contain graptolites, especially *Monograptus* of the *colonus* type. At the top lies the Aymestry Limestone, with *Pentamerus knighti*, *Dayia navicula*, etc.

The Upper Ludlow shales are also soft grey shales, with thin bands of limestone. They contain brachiopods and trilobites, but no graptolites. Towards the top they become more sandy, and include a thin bed, the Ludlow 'Bone-bed,' full of the bones and spines of fish and fragments of Eurypterids. It has been suggested that the boundary between the Silurian and Old Red Sandstone systems should be drawn here.

Downton Series.—At the top of the system are the Downton beds, consisting chiefly of sandstones, with some intercalations of shale. The colour is grey at the base, but becomes purple towards the top, where the beds pass upwards into the Old Red Sandstone. Eurypterids and remains of fish are the characteristic fossils, but *Lingula cornea* and other shells also occur, probably indicating brackish water conditions as a transition to the fresh-water lakes of the Old Red Sandstone of this area.

It has already been pointed out that the development of the Silurian system in the original area in the Welsh Borderland is by no means typical of the rest. However, the same type with conspicuous limestones appears in the Malvern Hills, in the inliers of Woolhope and May Hill in Hereford and Gloucester and even in the middle of the South Staffordshire coalfield. All these areas are to the east of what may well be called the *Stretton Line*, namely, the great N.E.–S.W. fault that now separates the Longmynd from the Wrekin range, and was a dominant feature of Lower Palaeozoic tectonics from a very early date. West of this line, in Wales, the Silurian system consists of great but variable thicknesses of grits, flags and shales, whose distribution is controlled by the trend of the shore-lines of the great geosynclinal already described. As an example of the dominant effect of this structure it may be mentioned that at Conway, in the deep water near its central axis, the Llandovery series with all its graptolite zones is only 300 feet thick, whereas round Plynlimon in central Wales the same zones have expanded to nearly 10,000 feet. Similar facts apply, though perhaps in a less exaggerated form, to the other series of the system. The central parts of Wales consist mainly of a monotonous series of Silurian grits and shales, without even the relief of volcanic intercalations as

in the Ordovician, and no good purpose would be served by a laborious attempt to indicate their local distribution and to enumerate the endless names that have been applied to their subdivisions. The broadest generalisation that can be made is that, besides the great variations in thickness, the graptolitic facies is dominant in the west, towards the centre of the geosyncline, and the shelly facies on the east, nearer the Stretton Line, while to the east of this extended a shallow sea dotted with coral reefs in which the limestones were formed.

In South Wales the Silurian is usually complete, passing up into the Old Red Sandstone by way of the Downton Series, which itself gradually takes on the characteristics of arid sedimentation as shown by the increasing redness of the upper members. In North Wales, however, this highest series of the system is missing. In Denbighshire nothing is known higher than about the middle of the Ludlow.

The calcareous facies appears in full force in the dome-shaped inliers of Woolhope and May Hill in Herefordshire and Gloucestershire and also on the western side of the Malvern Hills, where the strata are in places inverted, as a result of the great westerly overthrust. In these areas all three limestones, Woolhope, Wenlock and Aymestry are present, whereas the Woolhope Limestone is not seen in Shropshire. A classical occurrence of Wenlock Limestone, whence many of the best fossils in museum collections were obtained, is in the middle of the South Staffordshire coalfield, especially at Dudley, in the form of small domes brought up by the crossing of Caledonian and Charnian fold-lines. The limestone was extensively quarried, partly underground, for use as a flux in the local blast-furnaces and it seems to have been nearly exhausted.

Around Tortworth, north of Bristol, is a considerable area of Silurian rocks. Here the succession is less calcareous and an unusual feature is a mass of basic lava low in the Llandovery. In the Mendips again, Silurian rocks with igneous intercalations have been found in the cores of the Armorican folds, mostly exposed in rabbit-holes. This is the most southerly occurrence known in western England, but Silurian rocks have been found in several bores only a few hundred feet below sea-level in the south-east, as for example at Ware in Hertfordshire and in Kent. It is evident that Lower Palaeozoic rocks, considered as a whole, form part of the London Plateau and are continuous below ground with those of the Brabant Plateau of Belgium, which come to the surface south of Brussels. Silurian rocks are also exposed by the great Faille du Midi overthrust in eastern Belgium.

Northern England

The most southerly outcrop of Silurian rocks in this region is in the small but interesting Ribblesdale inlier, just north of the Craven fault system, where Ingletonian, Ordovician and Silurian rocks have been

successively jammed up against the resistant block of ancient rocks underlying the northern Pennines. Lithologically the Silurian rocks here are dull, as they consist mainly of a great thickness of flags and fine sandstones, commonly called grits, although they are not gritty, but the interest lies in the admirable exposure of the topography of a moderately folded series of hard rocks.

In the Lake District and in the adjoining Howgill Fells on the south-east, extending into Yorkshire, the development of the Silurian system is definitely of the geosynclinal type, with few calcareous beds. The base rests conformably on the Ordovician.

The Stockdale Shales, which represent the Llandovery, are only about 250 feet thick. They consist of black graptolitic shales below, often called the Skelgill Shales, and greenish shales, above, of the Tarannon facies, called the Browgill Shales, though the subdivision is unnecessary. It is remarkable that a bright green band in the lower part, not more than an inch thick, has also been found on the same zonal horizon in central Wales. The Stockdale Shales are well seen near the heads of Windermere and Coniston Water.

The Brathay Flags of Wenlock age comprise about 1,000 feet of blue-grey laminated mudstones with gritty partings and few fossils.

The remainder of the system consists of perhaps 12,000 feet of grits, sandstones, flags and shales, with occasional bands showing Ludlow fossils. They are usually subdivided into four series, from below upwards, thus: Coldwell Beds; Coniston Grits; Bannisdale Slates; Kirkby Moor Flags. For our present purpose the old name of Coniston Flags and Grits may conveniently be revived for the whole Wenlock and Ludlow succession.

The relative thicknesses of the three series as given above—250, 1,000 and 12,000 feet, are of interest, as indicating the rapid filling up of the geosynclinal in its later stages: there is no representative of the Downton series in the district, so that so far as northern England is concerned, this infilling may be regarded as the end of the story.

Scotland

In the Southern Uplands of Scotland Silurian strata form the south-eastern part of the broad belt of Lower Palaeozoic rocks running from sea to sea, from Galloway to Berwickshire, and they just extend over the Border in the Cheviot Hills. What has already been said as to the structure of the region in the chapter on the Ordovician system applies equally to the Silurian, as the two systems are conformable and are folded up together: it is true to say that the northern half consists of Ordovician rocks with outliers of Silurian, and the southern half of Silurian with inliers of Ordovician. There are also Silurian inliers in the central valley. In the main outcrop the system is incomplete, only the Llandovery and Wenlock being represented.

The Llandovery series shows a remarkable change of facies upwards; the lowest division, the Birkhill Shales, only 100 feet thick, includes six graptolite zones, and is a direct continuation of the Glenkiln and Hartfell Shales of the Ordovician and of exactly the same facies. But the rest of the series has expanded, even in the central belt, into the Gala group which is over 3,000 feet thick and consists of grits and flags, with occasional graptolitic shales: this great thickness includes only three zones. It corresponds to the Tarannon facies of Wales. The black shales have not a wide extent and at Girvan on the west coast the whole of the Llandovery is represented by a varied collection of shallow-water deposits: conglomerates, sandstones, grits, limestones and grey shales with abundant brachiopods, trilobites, molluscs and corals; the typical shelly facies. The whole is generally known as the Newlands series, though several local group-names are applied to lithological subdivisions. The whole of the Llandovery here also affords a remarkably clear illustration of the filling of the geosyncline.

In the equivalents of the Wenlock Series there is little variation of facies over the whole area, and the rocks consist chiefly of conglomerates, greywackes, grits and shales of shallow water origin. The total thickness of this, the Riccarton group, is about 2,000 feet. Fossils belong to both the shelly and graptolitic types intermixed, but no graptolites of the *colonus* group have been found and it is doubtful whether even the whole of the Wenlock is represented.

The higher beds of the system are not known in the Southern Uplands, but they are exposed amongst the later deposits which cover the Scottish Midland Valley. These inliers form two groups, one towards

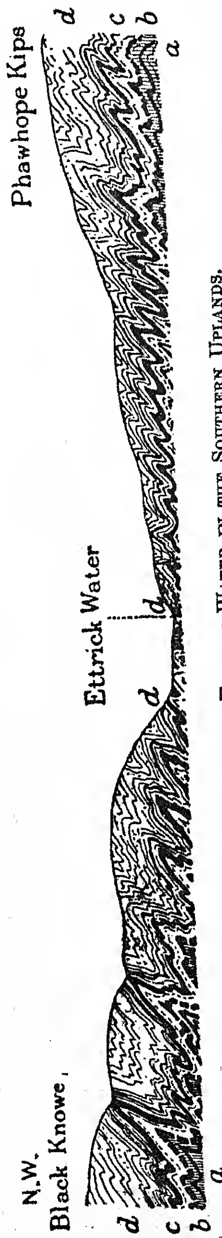


Fig. 110.—Section across Ettrick Water in the Southern Uplands.

(From the *Memoirs of the Geological Survey*, 'Silurian Rocks of Britain,' Vol. i. Reproduced by permission of the Controller of H.M. Stationery Office.)

a, Glenkiln Shales; *b*, Hartfell Shales; *c*, Birkhill Shales; *d*, Tarannan or Gala series.

the west in Lanarkshire and Ayrshire, the other towards the east in the Pentland Hills (Fig. 110). In both areas the deposits consist of shales, flagstones and sandstones, becoming red and green towards the top. Many fossils have been found in them, including eurypterids, phyllocarids, scorpions, fishes, etc., and they clearly represent the Upper Ludlow and Downton sandstone of the Welsh borders. In Lanarkshire they seem to pass up quite gradually into the Old Red Sandstone; but in the Pentland Hills the Old Red Sandstone rests upon their upturned edges. Ludlow rocks are also known near Stonehaven, on the line of the Highland fault.

Ireland

Both facies of the Silurian are found in Ireland, the former in the west and the latter towards the north and east. In the north-eastern area, which is the continuation of the Scottish Silurian belt, Llandovery rocks predominate, and they resemble the Birkhill shales and Gala series of the Southern Uplands. Towards the south of the area, in County Louth, Wenlock beds like those of Scotland have been found. The large inliers of Tipperary and the surrounding counties are also formed, in part at least, of graptolitic beds. Near the western coast, however, in Galway, Mayo and Kerry, the graptolitic facies disappears and the deposits consist of conglomerates, sandstones, flags and shales. The flags and shales are often calcareous, but no pure limestone is found, and no black graptolitic bands. Brachiopods become the dominant type of fossils. Possibly because the sandy type of deposits extends to a higher horizon than elsewhere, the Llandovery forms *Pentamerus oblongus* and *Stricklandia lens* have been found associated with species which in Wales belong to the Wenlock series. In the Dingle Promontory the Wenlock beds include a considerable development of rhyolitic lavas and ashes.

The structure of the great belt of Ordovician and Silurian rocks that runs across southern Scotland and north-eastern Ireland is extremely complicated in detail, but when analysed its leading features are found to be a fan or anticlinorium on the north-western side and a corresponding inverted fan or synclinorium on the south-eastern side (see Chapter X, p. 213). This structure is one of the more conspicuous results of the Caledonian earth-movements, which reached their climax in the Old Red Sandstone period, but began to show their effects before the end of the Silurian, thus accounting for the absence of the higher divisions of that system in the northern regions, as is shown in the table:

Salop.	North Wales.	Lake District.	South Scotland.
Downton Series	—	—	Eurypterid Beds
Upper Ludlow Aymestry Limestone Lower Ludlow	—	Coniston Flags and Grits	—
Wenlock Limestone Wenlock Shale Woolhope Limestone	Denbighshire Flags and Grits		Riccarton Series
Upper Llandovery	Tarannon Shales	Stockdale Shales	Gala Grits
—	Corwen Grits		Birkhill Shales

Correlation Table of the Silurian System (much simplified).

CHAPTER XIX

THE DEVONIAN AND OLD RED SANDSTONE SYSTEM

Although it is only here and there that the rocks of the three preceding systems now appear upon the surface, originally the deposits covered the greater part of the British Isles. The Devonian, on the other hand, was discontinuous from the first. It was laid down in isolated basins separated by regions in which denudation exceeded deposition. So far as the area was concerned, the three preceding periods were marine; the Devonian was in part continental.

The rocks of this system are found in the following districts (Fig. 111):

1. Cornwall and South Devon.
2. North Devon and West Somerset.
3. South Wales and the bordering counties.
4. Cheviot area.
5. Midland Valley of Scotland.
6. Orcadian area (shores of the Moray and Dornoch Firths, Caithness, Orkneys, Shetlands).
7. Argyll.
8. North Ireland.
9. South Ireland.

It must not be assumed, however, that all these areas were originally distinct. In some cases they have been separated by subsequent denudation.

There are two entirely different developments of the system. In Devon and Cornwall it consists chiefly of dull-coloured sandstones, slates and limestones, with trilobites, brachiopods and corals, not differing in their general character from the Silurian rocks. North of the Bristol Channel the system is formed of brightly-coloured red and brown sandstones and marls. Neither brachiopods nor corals are found in these deposits, and the arthropods are represented not by trilobites but by the giant Eurypterids. The most important fossils, however, are the remains of plants and of armoured fish. These rocks are not of marine origin, but fresh-water or terrestrial.

The first of these facies is known as the Devonian type, the second as the Old Red Sandstone type. Very few fossils are common to the two, but some of the fish, such as *Pteraspis*, are found both in the Lower Devonian of South Devon and in the Lower Old Red Sandstone of South Wales. There is, however, but little direct palaeontological evidence that the two kinds of deposit were contemporaneous; and

it is chiefly from their stratigraphical position that their equivalence is inferred. In Wales the Old Red Sandstone passes downwards conformably into the Silurian, and upwards into the Carboniferous. In

FIG. 111.—THE DEVONIAN AND OLD RED SANDSTONE SYSTEM.

Devon and Cornwall the relations of the Devonian to the Silurian are still obscure, but upwards the Devonian beds pass quite conformably into the Carboniferous. In Scotland also the Old Red Sandstone

passes upwards into the Carboniferous; and some of the red beds belong to that system. In the north of Russia, deposits of the Old Red Sandstone type lie between the Silurian and the Carboniferous. In Belgium, Germany, France and Southern Europe, rocks of Devonian type occupy a similar stratigraphical position. There can be no doubt, therefore, that on the whole the Devonian and the Old Red Sandstone are approximately equivalent; but it is by no means certain that the Old Red Sandstone facies ceases everywhere at the same horizon. There is, in fact, a considerable amount of evidence that towards the north it persists into the earlier stages of the Carboniferous, and some definitely red beds are classed with the Silurian: e.g. the Downtonian.

The Devonian rocks, with their fauna of brachiopods, trilobites and corals, are normal marine sediments. But the absence of any of these forms in the Old Red Sandstone indicates that the red beds were laid down under different conditions. Sometimes they are conglomerates or breccias, sometimes they are current-bedded sandstones, sometimes fine flags showing ripple-marks and sun-cracks; but always they bear evidence that they were formed in shallow water or upon the surface of the land itself. The bright colours also, though by no means universal, differentiate the Old Red Sandstone from any ordinary marine deposits, and are characteristic at the present day of the sediments of dry or desert regions. The presence of plants, which in some places are very abundant, shows the existence of land.

These considerations have led to the belief that while the Devonian rocks were laid down in the open ocean, the Old Red Sandstone was deposited in intermont basins, or in inland waters which perhaps were originally arms of the sea cut off by the crumpling of the earth's crust during this period.

The Old Red Sandstone facies is characteristic of Northern Europe, extending southwards to the latitude of the Bristol Channel, and even further south in Russia. In Central and Southern Europe the Devonian facies alone is found. Hence it may be inferred that a land mass lay in the north, bearing upon its surface sheets of water, while in the south spread the open sea. At times the southern ocean encroached upon the margin of the northern continent, and here to a certain extent the two facies are interstratified. In North Devon, for example, and still more in Russia, red sandstones with remains of fish occur in the midst of slates with brachiopods. In general, however, the limits are very sharply defined.

The period was one of violent earth-movements and of great volcanic activity. It was in Devonian times that the overthrusts of the Scottish High ands and of Western Scandinavia were formed, and most of the folding of the Lower Palaeozoic rocks of Scotland, the Lake District and the north of Wales took place. The general direction of the folds is N.E.–S.W., and the result of the movements was the elevation of

a mountain range in Northern Europe, of which Norway and most of the British highlands are the worn and broken stumps. This ancient mountain range has been called by Suess the Caledonian Chain (see also Chapter XXVII).

In Scotland the crumpling of the crust was accompanied by extensive volcanic eruptions; so that in some districts the Old Red Sandstone is formed very largely of lavas and agglomerates. There is no sign of these in South Wales, where the conditions appear to have been more tranquil; but volcanic beds are interstratified with the marine deposits of South Devonshire. There was also great intrusive activity in Scotland, northern England and Ireland (see Chapter XXVIII).

Fauna.—In its general character the fauna of the marine Devonian is similar to that of the Silurian, and many of the Silurian genera still survived.

The most important difference, perhaps, is the entire absence of graptolites, which are last seen in the Ludlow beds. *Stromatopora* and its allies, on the other hand, which are believed to belong to the same class of the animal kingdom, become more abundant.

Corals take a large share in the formation of the limestone bands. Many of the genera occur also in the Silurian rocks, e.g. *Favosites, Heliolites, Acervularia*; others, such as *Calceola* and *Pleurodictyum*, are peculiar to the Devonian; while some, like *Phillipsastrea*, make their first appearance in these rocks, but range upwards into the Carboniferous. Crinoids also are common in the limestones, *Cyathocrinus* and *Cupressocrinus* being two of the genera represented. Brachiopods occur abundantly not only in the limestones, but also in the slates and grits. The genera *Stringocephalus* and *Uncites* are peculiar to the Devonian; of the other forms, *Orthothetes, Spirifer, Rhynchonella* and *Atrypa* are the most important. Some of the characteristic Carboniferous genera, such as *Productus*, begin to appear in the higher beds. Mollusca are common in some of the beds. Stratigraphically, the most important are cephalopods belonging to the suborder Ammonoidea. *Clymenia* is entirely confined to this system. The group commonly known as goniatites makes its first appearance, and is represented by the genera *Mimoceras* and *Anarcestes*. Trilobites are very much less abundant, both in species and in individuals, than in the Silurian rocks. Several of the genera, e.g. *Dalmanites* and *Homalonotus*, show a tendency to develop spines upon the head, thorax or tail—a tendency which in other groups of animals has proved to be a sign of decadence. The commonest forms are *Dalmanites* (*Cryphaeus*), *Phacops, Homalonotus, Pröetus* and *Bronteus*. A few of the fish characteristic of the Old Red Sandstone facies are found also in the marine Devonian. Of these, the genus *Pteraspis* appears to be the commonest.

As a rule, the Old Red Sandstone facies is not very fossiliferous, but in some localities and at some horizons the remains of eurypterids, fish

and plants are found in great abundance. Of the eurypterids, *Eurypterus*, *Pterygotus* and *Stylonurus* are the principal genera. The fish include representatives of the Elasmobranchii, Ostracodermi, Ganoidei and Dipnoi. The most striking forms are those in which the head and the anterior portion of the trunk is protected by large plates, forming a more or less rigid coat of armour. Amongst these are the genera *Pterichthys*, *Cephalaspis* and *Coccosteus*. Other forms, such as *Holoptychius*, are less abnormal in shape, and bear overlapping scales, but the paired fins are each provided with an axis which is covered with scales. The plants are mostly lycopods and ferns, including such forms as *Knorria* and *Palaeopteris*. In the higher beds the lamellibranch *Archanodon jukesi* has been found in several localities. From its general resemblance to the living *Anodon*, it is supposed to have lived in fresh water.

Cornwall and South Devon

Between the Lizard or Meneage crush-zone (see p. 309) and a line drawn east and west approximately through Truro is an area of highly crushed sediments of uncertain age, the *Killas* of the mining district of West Cornwall. This is divided into the Mylor series above and the Gramscatho below, the latter name being a portmanteau word, made up from Grampound and Portscatho, the names of two former subdivisions now combined. They are generally believed to be Lower Devonian, equivalent to some of the better defined fossiliferous rocks to the north.

The whole of Cornwall and Devon was subjected to intense compression during the Armorican earth-movements, and the structure has proved very difficult to unravel. The major subdivisions in the more clearly defined area are characterised as follows:

The Lower Devonian consists chiefly of slates and grits. The slates are sometimes dark in colour, sometimes green or purple. The grits are variable, but attain their greatest development in the upper part of the series. Volcanic rocks occur, but not to so great an extent as in the Middle Devonian. The fossils are usually distorted. They include *Dalmanites* (*Cryphaeus*) *laciniatus*, *Spirifer hystericus* and the peculiar coral *Pleurodictyum problematicum*.

The Middle Devonian also consists very largely of slates, but the amount of gritty material is less, while volcanic tuffs and calcareous bands assume a greater importance. Locally, as at Torquay, the limestones attain a considerable thickness and form the greater part of the series. The volcanic rocks occur at various horizons, and reach their greatest development south of Totnes. The lower beds of the series contain *Calceola sandalina*; the limestones above contain a very abundant fauna, including *Stringocephalus burtini*, *Uncites gryphus*, numerous corals, etc.

The **Upper Devonian** is formed in part of grey massive limestones with *Rhynchonella cuboides* and several species of goniatites. These are followed by red slates with *Clymenia* and the small crustacean *Entomis serrato-striata.*

The fauna of the whole is typically Devonian, but some of the characteristic Old Red Sandstone fish, especially *Pteraspis,* occur in considerable abundance at certain horizons. The fossils are closely similar to those of Belgium and northern France and the beds have been correlated with their continental equivalents in the standard classification, which need not be given here.

North Devon

In the north of Devonshire and the west of Somerset the Devonian system forms a broad belt along the southern shores of the Bristol Channel extending from Barnstaple Bay on the west to the Quantock Hills on the east. It consists in part of red or yellow sandstones, containing remains of plants and fish, in part of grey, green or purple slates with brachiopods and other marine fossils. Calcareous bands occur, especially in the middle of the formation, but they are nowhere so thick or so massive as the limestones of South Devon. The Devonian of North Devon is, in fact, an intermediate type, belonging partly to the Old Red Sandstone facies and partly to the true marine Devonian. In the Quantock Hills and the Mendips in Somerset, it is of the Old Red facies.

The strike of the rocks is very regular, and the beds crop out in a series of parallel bands running east and west. They are, however very greatly folded ; but as the prevailing dip is towards the south, the oldest strata lie at the northern margin of the belt, and the succeeding beds follow in regular order towards the south. The succession is as follows (in descending order) :—

8. Pilton Beds. Bluish-grey slates with thin bands of limestone and sandstone ; very fossiliferous. *Phacops latifrons, Productus praelongus, Spirifer verneuili.*
7. Baggy Beds. Greenish shales and sandstones. *Ptychopteria damnoniensis, Cucullaea hardingi,* and plants (*Knorria,* etc.).
6. Pickwell Down Sandstone. Red and purple sandstones. Remains of fish and plants.
5. Morte Slates. Greenish-grey glossy slates, much veined with quartz. *Spirifer verneuili.*
4. Ilfracombe Beds. Grey slates and flags with impure bands of limestone. *Stringocephalus burtini, Cyathophyllum caespitosum, Heliolites porosus,* etc.
3. Hangman Grits. Red grits and sandstones. Casts of lamellibranchs and gastropods in the upper beds.
2. Lynton Slates. Grey and purple slates and grits. *Spirifer laevicosta, S. hystericus, Orthis arcuata.*
1. Foreland Sandstone. Red sandstones and grits. Remains of plants.

As is shown in this table, the formation consists chiefly of slates with three main bands of red sandstone, viz. the Foreland Sandstone, the Hangman Grits, and the Pickwell Down Sandstone.

The broad-scale structure of the Devonian rocks of south-west England is a synclinorium of Armorican date, the space intervening between the two main outcrops being occupied by conformable Carboniferous rocks. Eastwards the whole structure disappears under unconformable New Red Sandstone, striking N.–S. but rocks of Devonian age have been identified in several deep bores in the London area, whence they are continued underground till they reappear in France and Belgium in the South Devon facies.

South Wales and the Welsh Borderland

In Wales and the neighbouring counties is a large triangular area of rocks of this age with its base on the western side of the Severn Valley and its apex in Pembrokeshire. Over most of the area the lower beds are continuous with the Silurian and the upper beds pass up into the Carboniferous. The North Devon facies of the marine Devonian extends more or less into the south of Wales, though the deposits were laid down in still shallower water and there may have been some kind of a partial barrier along the line of the Bristol Channel. Further north they were deltaic or even terrestrial, indicating the uprise of a land area to the north in late Silurian times. In the middle of the period there was a powerful uplift, causing a non-sequence, and the Middle Old Red Sandstone of Scotland is not represented.

Some geologists have lately assigned the Downtonian of Shropshire to the Old Red Sandstone, but it is here retained in the Silurian. As thus defined the lowest part of the system is the Dittonian, sandstones and cornstones with fish remains. (Cornstones are concretionary and mechanical limestones). The upper part of the Lower division west of Abergavenny has been divided into the Senni beds (micaceous, flaggy sandstones, shales and marls) below, and the Brownstones (brown sandstones) above. Further south the Dittonian is mostly red marls and red conglomerates in the lower part, and above these comes the Cosheston Sandstone of Pembrokshire which attains a thickness of 10,000 feet.

The Upper Old Red Sandstone of Pembrokeshire consists of the Skrinkle Sandstones, which contain some fossils like those of the Baggy beds of North Devon. To the north-east it passes into sandstones with fish remains. Near Abergavenny a fresh-water mollusc, *Archanodon jukesi*, has been found.

The most important fossils of the Lower division are the fish *Pteraspis* and *Cephalaspis*, and in the upper *Holoptychius*. Eurypterids, often of

great size, are characteristic of the period, as well as of the Downtonian. Plant remains are fairly common in certain beds.

Northern England

It is commonly stated that in Northern England there is no Old Red Sandstone (the Cheviot area just extends into Northumberland). There are, however, in several places in West Yorkshire, Westmorland and Cumberland considerable masses of red conglomerates, usually assigned to the base of the Carboniferous. In several of these localties, e.g., Shap, Sedbergh and Cross Fell, there are clearly two conglomerates, of quite different composition, the lower being almost certainly of Old Red Sandstone age. The largest occurrence is in Cumberland, where the Mell Fell conglomerate, well seen at the foot of Ullswater, has a maximum thickness of at least 800 feet.

Scotland

The Old Red Sandstone in the south of Scotland differs considerably from that of the north, and it is probable that there were at least two separate areas of deposition. The southern type occurs in the Cheviot district, in the Midland Valley of Scotland and in Argyll. The northern, or Orcadian, type is found in the Orkneys and Shetlands, in Caithness, and on the shores of the Moray Firth. In the southern type the Middle Old Red Sandstone is absent, there is a strong unconformity between the Lower and the Upper divisions, and in the Lower Old Red Sandstone there is a great development of volcanic rocks. In the northern type the Middle Old Red Sandstone is by far the best developed; the Lower division of the system is entirely absent, while the Upper is limited to a few comparatively small tracts and rests unconformably upon the Middle division. Moreover, in this northern area there was very little volcanic activity during the Old Red Sandstone period.

The Cheviot Area

In this region the Old Red Sandstone lies chiefly on the Scottish side, but it also extends south of the border into Northumberland. It rests unconformably upon the folded Silurian rocks, and consists of red sandstones and marls, together with beds of lava, tuff and agglomerate. In the Cheviot Hills themselves the volcanic rocks attain a thickness of a couple of thousand feet. No fossils have been found excepting remains of plants and eurypterids, but the whole series is referred to the Lower Old Red Sandstone.

Resting unconformably upon these beds there is a second series of red sandstones and marls, with a basement conglomerate or breccia.

It is uncertain how much of these belongs to the Old Red Sandstone and how much to the Carboniferous. But *Palaeopteris hibernica* and scales of fish have been found in the lower part.

Midland Valley of Scotland

The Old Red Sandstone and the succeeding Carboniferous beds form the lowland belt which stretches from north-east to south-west across the centre of Scotland, between the Highlands on the north and the Southern Uplands on the south. The middle of the belt is occupied by the Carboniferous deposits, and the Old Red Sandstone appears along its northern and southern margins.

The system is separated into an Upper and a Lower series, no Middle Old Red Sandstone being present in this area. The Lower series, which is much the thicker, reaching a maximum of nearly 20,000 feet, includes a great development of igneous rocks, as in the Ochil and Sidlaw Hills on the north and the Pentlands on the south. The chief types of lava are olivine-basalt, basalt and andesite, and there are innumerable intrusive sills and dykes. The sediments include sandstones, flags, marls, grits, and an extraordinary development of conglomerates, the pebbles on the north side coming from the Highlands and on the south side from the Southern Uplands. This great series was laid down in an intermont basin bounded by faults, really a great rift valley, under semi-arid conditions, with the formation of torrential gravels and boulder-deposits, and occasional pools where finer sediment was laid down. In this area volcanoes were numerous.

After a period of uplift and denudation giving rise to a strong unconformity, the Upper division was formed under much the same conditions, except that there were no volcanoes. The land was low-lying and often flooded, with rivers and temporary lakes ; sometimes almost a desert, giving rise to the formation of red sandstones, shales and marls, with grits and conglomerates. This series is not more than 3,000 feet thick. The only fossils are fish, many being the same species as in Wales. The most famous fossil fish locality is Dura Den, near Cupar in Fife. In places the Upper series overlaps on to the Silurian and even on to the Highland schists, showing that it is later than the metamorphism of the Caledonian revolution.

Argyllshire

There is a small area of Old Red Sandstone at Oban consisting of andesitic and trachytic lavas and ashes, shales, sandstones and conglomerates, containing very large boulders. The lavas involved in the Cauldron Subsidence of Glencoe are of the same type. All of these must belong to the Lower Old Red Sandstone, since they are clearly older than the granitic intrusions of the Caledonian revolution, which does not metamorphose the Upper division in other localities.

Orcadian Area

The Old Red Sandstone forms a coastal strip around the shores of the Moray and Dornoch Firths; it spreads over the greater part of Caithness and the Orkneys, and occurs also in the Shetland Isles.

The lower division of the system is absent and the **Middle Old Red Sandstone** lies directly upon a denuded and uneven floor of crystalline schists, granite, etc. Where the deposits rest upon this floor, or abut against its slopes, they are coarse and conglomeratic; but elsewhere they are for the most part fine-grained, sandy, clayey, calcareous or bituminous flags, often showing sun-cracks and ripple-marks. Clearly they were laid down in tranquil waters, and the conglomerates were formed as beaches. Towards the top of the series the deposits become more siliceous and form definite sandstones.

Excepting in the Shetlands, there are only one or two sporadic outbursts of volcanic rock. In some places the remains of fish are very abundant. *Thursius*, *Dipterus* and *Coccosteus* are amongst the genera found.

The **Upper Old Red Sandstone** consists of yellow and red sandstones resting unconformably upon the lower division. They contain *Holoptychius*, *Coccosteus* and other fish. In the Orkneys there are beds of lava and volcanic ash near the base of the series.

Ireland

The Irish areas of Old Red Sandstone may be divided into two groups. In the north is the continuation of the Caledonian area, most conspicuously developed in the counties of Tyrone and Fermanagh. In the south the Old Red Sandstone appears to be the continuation of the Welsh deposits, and forms the principal heights and mountains of Munster.

The Old Red Sandstone consists chiefly of brown and purple conglomerates with beds of grit and sandstone, and generally rests unconformably upon the older rocks. In the south of Ireland these conglomerates are followed by a series of fine-grained yellow sandstones known as the Kiltorcan beds, which pass upwards conformably into the Carboniferous. These sandstones have evidently been deposited in tranquil water, and in Kilkenny they contain a freshwater fauna and terrestrial flora of Upper Devonian age. *Archanodon jukesi* and *Palaeopteris hibernica* are amongst the fossils that have been found, together with remains of *Coccosteus* and other Old Red Sandstone fish.

In the south of Ireland there are also other deposits which may belong to this period. In the Dingle Promontory the Silurian beds are apparently succeeded by a great thickness of grits, sandstones and slates known as the Dingle beds. They contain no fossils except such as have been derived from older beds, and they are overlaid unconform-

ably by Old Red Sandstone conglomerates; but they may belong to an earlier part of the period. It is possible, however, that their apparent position in the succession is due to faulting and folding.

In County Cork the lower part of the so-called Carboniferous Slate includes bands of sandstone with a marine fauna, called the Coomhola Grits. The fossils found in them are similar to those in the Baggy beds of North Devon, apparently indicating that the extreme south-west of Ireland, like North Devon, lay upon the border of the Devonian sea.

The extremely important earth movements and igneous activity of the Devonian and Old Red Sandstone age, the Caledonian revolution, are described briefly in Chapters XXVII and XXVIII.

CHAPTER XX

THE CARBONIFEROUS SYSTEM

The Carboniferous rocks of England (Fig. 112) are affected by two systems of folds and faults, running respectively from north to south and from east to west. By these folds they are thrown into a series of basins, which in some cases still remain connected but in others have been completely isolated by subsequent denudation.

In the north of England the dominant fold is an anticline, which runs from Derbyshire northwards and ultimately becomes a fault on the western limb. In consequence of this the Carboniferous system forms a broad belt extending down the middle of the country from Berwickshire to Derbyshire. In the Midland plain the Carboniferous beds are to a large extent concealed by newer deposits, but through these they appear occasionally as inliers. Upon the western margin of the plain they crop out in a narrow strip resting against the old rocks of the Welsh borderland; and several outliers occur still further west. In the south, the east–west folds begin to prevail. In South Wales the Carboniferous beds form an elongated basin with its axis running from east to west. They form another basin in the Forest of Dean, and a somewhat complicated system of folds in Gloucestershire and Somerset, including the Bristol coal-field and the Mendip Hills. In Devonshire the Carboniferous strata occupy a broad syncline between the Devonian rocks of the north and south of the county. In Scotland the Carboniferous beds form a large part of the Central Lowlands, extending completely across the country from the Firth of Forth to the coast of Ayr. Carboniferous rocks cover the greater part of Ireland. They form almost the whole of the central plain, and although interrupted by the appearance of older rocks in the cores of anticlinal folds, they stretch south-westwards through Munster. Only in the north and the south-east of the country are there any extensive areas from which the Carboniferous beds have been entirely removed.

The Carboniferous system of the British Isles may be divided into two series. In the earlier part of the period marine conditions prevailed, and great masses of limestone were formed. In the latter part the area became land, and deposits of sandstone, shale and coal were laid down. It was formerly customary to divide the system into—

Coal Measures,
Millstone Grit,
Carboniferous or Mountain Limestone;

but it was recognised that terrestrial conditions began much earlier in the north than in the south, and that in Scotland even the lower division contains fresh-water beds and seams of coal. So marked,

FIG. 112.—THE CARBONIFEROUS SYSTEM.

however, in general is the difference between the beds below and the beds above the Millstone Grit that the former were commonly spoken of as the Lower Carboniferous, while the Millstone Grit

and the Coal Measures were grouped together as the Upper Carboniferous.

It was doubtful, however, whether the beds known as the Millstone Grit were everywhere at the same horizon, and it has since been proved that sandstones of various ages have been included under this name. The division into Lower and Upper Carboniferous is still retained, but the base of the Millstone Grit can no longer be accepted as the dividing line.

Taking the Carboniferous system of Britain as a whole the general succession is—

(*c*) Shales and sandstones with coal.
(*b*) Sandstones and shales without coal.
(*a*) Limestones and shales.

This sequence indicates a transition from marine to terrestrial conditions. The most important conclusion drawn from a comparison of all areas is that each of the later facies appears earlier in the north, owing to initial tilting of the basement. In Northumberland coal appears at the top of the Lower Carboniferous, and in Scotland much coal is worked about the middle of the Lower Carboniferous.

The international classification of the Carboniferous of Western Europe is as follows:

Upper	Stephanian. Westphalian. Namurian.
Lower	Visean. Tournaisian.

On the Continent the Namurian, which is nearly equivalent to our Millstone Grit, has till lately usually been included in the Westphalian. In America the equivalents of the European Carboniferous, which in the eastern States are very similar, are divided into two systems, the Mississippian below and the Pennsylvanian above, corresponding to our Lower and Upper Carboniferous.

LOWER CARBONIFEROUS OR AVONIAN.[1]

The Lower Carboniferous forms the rim of all the Carboniferous basins excepting those of the Midlands; it forms also the central and broadest portion of the belt which runs from Derby to Berwick; it occupies a large part of the Central Lowlands of Scotland; and it covers nearly the whole of the Irish plain.

Typically it is a limestone formation, and its most prominent member is commonly known as the Carboniferous or Mountain Limestone.

[1] Some British geologists use the Belgian name Dinantian, which is equivalent to Avonian.

But towards the north it loses its calcareous character and becomes a succession of sandstones and shales with only subordinate beds of limestone. In the Midland plain it is absent or much reduced in thickness. In Devonshire it is represented chiefly by shales and cherts.

Fauna.—The fauna of the Lower Carboniferous is rich and varied in character. Corals, brachiopods and crinoids are the most abundant forms, the limestones being made up to a very large extent of their remains. Of the corals, the genera *Lithostrotion*, *Lonsdaleia*, *Clisiophyllum*, *Cleistopora*, *Zaphrentis*, *Cyathophyllum* and *Syringopora*, are amongst the most important. The first three are confined to this system. The crinoids include a number of genera which survived from the preceding period, and also *Actinocrinus*, *Amphoracrinus* and *Woodocrinus*, which appear for the first time. Another group of echinoderms—the Blastoidea (e.g. *Granatocrinus*)—attain their maximum development in these rocks; and there are several genera of echinoids, such as *Archaeocidaris* and *Palaeechinus*. Of the brachiopods, *Productus* (*P. giganteus*, *P. semireticulatus*) is the most characteristic genus, although it is not confined to these beds. Other important genera are *Spirifer* (*S. striatus*), *Rhynchonella* (*R. acuminata*), *Athyris*, *Terebratula* (*T. hastata*). Lamellibranchs and gastropods are both abundant Amongst the former the genera *Conocardium* and *Posidonomya* (*P. becheri*); amongst the latter the genus *Euomphalus* (*E. pentangulatus*) may be mentioned.

The Cephalopoda include straight forms such as *Orthoceras* and *Actinoceras*, and also several genera of goniatites such as *Glyphioceras*. The last survivors of the trilobites are found in these beds; but they are not common, and they are generally small. *Phillipsia*, *Griffithides* and *Brachymetopus* are the genera most often met with; but a few other forms also occur occasionally. Another group of Crustaceans, viz. the Schizopoda, is abundantly represented in the Carboniferous of Scotland. Fish remains, especially teeth and spines, are common. They include elasmobranchs (e.g. *Psammodus*), ganoids and dipnoi, but no ostracoderms. The first amphibians occur in the Lower Carboniferous. They belong to the group of Labyrinthodonts. In the brackish and fresh-water deposits of the north, plants and lamellibranchs are found, some of which do not appear in the south until the Coal Measure period.

Flora.—The Carboniferous period was distinguished by exceptionally vigorous development in the plant world, as measured by the evolution of new forms and the production of a large number of new genera and species. In the Upper Carboniferous we see Palaeozoic vegetation at its zenith; it may be called the age of Pteridosperms and giant Pteridophytes. Although great advances have been made in recent years, there is still some uncertainty as to the systematic position and inter-

relationships of certain of these plants. Some of the genera are polyphyletic 'form-genera,' based purely on the shape of the vegetative organs, and no doubt include plants which are really not related to one another; and in other cases different parts of a single plant have been described under different generic names, e.g. *Lepidodendron* (stem), *Lepidostrobus* (fructification) and *Stigmaria* (root).

The physical conditions during the first half of the Carboniferous period were in most areas ill adapted to the preservation of samples of terrestrial vegetation as compared with those of the second half, when swamp and lagoon conditions prevailed. In the Lower Carboniferous calcareous algae are locally important as limestone builders, as *Girvanella* and *Solenopora*. Amongst the Lycopodiales, *Lepidodendron* is common but *Sigillaria* is rare. Of the Articulatae, *Sphenophyllum* and *Asterocalamites* occur but *Calamites* is uncommon. Pteridosperms are abundant, and include genera such as *Heterangium*, *Sphenopteridium*, *Adiantites* and *Cardiopteris*. True ferns, such as *Rhacopteris*, *Botryopteris* and *Clepsydropsis* are also fairly common. *Pitys*, *Archaeopitys* and *Psygmophyllum* are the commonest gymnosperms, Coniferaleans are rare, and Ginkgoaleans and Cycads unknown.

Classification of the Lower Carboniferous

The Lower Carboniferous beds change in character as they are traced across country, and particularly when they are followed from south to north. In Devonshire the series consists of radiolarian cherts, calcareous shales, and black limestones. In the Bristol and South Wales area it is mainly limestone, with shales at several horizons. Towards the north it thins out rapidly, till in South Staffordshire and Warwickshire it disappears entirely, and the Upper Carboniferous rests directly upon older rocks. But it reappears in Derbyshire, where it is again chiefly massive limestone, showing a thickness of more than 1,500 feet, although the base is not exposed. Along the Pennine Chain beds of sandstone and shale appear in the limestone, and rapidly increase in thickness, while the amount of limestone is reduced, until in Northumberland the series as a whole consists chiefly of sandstones and shales, with subordinate limestones and an occasional seam of coal. In Scotland the shallow-water character of the deposits is still more strongly marked, some of the beds containing fresh-water fossils, the seams of coal being of considerable thickness and importance.

From this general description it will be evident that during the period of the Lower Carboniferous the principal area of land lay to the north, in Scotland, and from there the sea deepened with local variations towards Derbyshire. Across the Midlands a ridge of land stretched from east to west, and against this ridge the Lower Carboniferous deposits thinned out on both sides; but south of it the sea again deepened towards Bristol. At one time it was supposed that the

radiolarian cherts of Devonshire indicated still deeper water in the south; but radiolarian cherts are often interbedded with shallow-water deposits, and cannot be considered as evidence of deep-sea conditions.

The lithological changes just described, indicating differences in the depth of the sea, are accompanied by changes in the character of the fauna. Consequently, there has always been considerable difficulty in correlating the beds of different areas, and it was not until 1904 that a zonal succession in the Lower Carboniferous was established.

It was in the Bristol area that a clear and definite palaeontological classification was first successfully attempted, and accordingly the Lower Carboniferous of Bristol has become the type for comparison with other areas. The zonal divisions are based on the corals and brachiopods, the most abundant fossils, and six zones are recognised, which for brevity are often referred to by letters, as shown in the following table (in descending order):

Avonian	Visean.	D.	*Dibunophyllum* zone.
		S_2.	*Seminula* zone.
		C_2S_1.	*Upper Caninia* zone.
	Tourn-aisian.	C_1.	*Lower Caninia* zone.
		Z.	*Zaphrentis* zone.
		K.	*Cleistopora* zone.

Each of these zones is further subdivided into sub-zones, for more detailed work, as Z_1 and Z_2 and so on. The symbols C_1,C_2S_1 and S_2 mean that the top half of the C zone and the lower part of S have been combined later to form a new zone. There were originally only five, C including all the beds with *Caninia* and *Syringothyris*, but it was found that this cut across the Belgian classification. The *Dibunophyllum* zone is divided into three sub-zones, D_1, D_2, and D_3: of these D_3 is part of the 'Millstone Grit' of Bristol. It was later found further north that calcareous beds overlying the equivalents of D_2 contain Lower Carboniferous fossils, a clear proof that the base of the Millstone Grit is not everywhere at the same horizon and will not do for the dividing line between Upper and Lower Carboniferous. Part of the 'Millstone Grit' of Bristol is Lower Carboniferous (Avonian), whereas in Yorkshire it is all Upper Carboniferous. This point will arise again later (see p. 374). Elsewhere calcareous D_3 beds contain a characteristic coral, *Cyathaxonia*, which is not found at Bristol.

It is now becoming customary to put K in the Devonian system, as the fossils are similar to those of the Upper Pilton Beds in Devonshire. As this zone is very doubtfully present anywhere north of Bristol the point is not of much importance.

Variations of the Lower Carboniferous

Devonshire.—The Carboniferous rocks of Devonshire consist of shales with bands of chert, limestone and impure coal. The latter is locally known as *culm*, and the whole succession is often called the Culm measures. The rocks are greatly folded, but it is now clear that the Culm measures may be divided into a lower division belonging to the Lower Carboniferous and an upper division corresponding with part of the Upper Carboniferous of other districts.

The lower division occupies a comparatively small area upon the margins of the Devon syncline, and includes two distinct series of beds, the one cherty and the other calcareous. The cherty beds, known as the Coddon Hill series, consist of thin-bedded, hard cherty rocks with intermediate beds of light-coloured siliceous shale. The cherts are formed of radiolaria, and several species of trilobites and numerous diminutive brachiopoda have been found. The calcareous beds consist of black shales and limestones, with *Posidonomya becheri*, *Glyphioceras spirale*, *G. crenistria*, etc. The precise horizon of the Coddon Hill beds is uncertain, but fossils of the calcareous beds also occur in the north, in strata that are undoubtedly Lower Carboniferous.

Bristol and South Wales.—The Lower Carboniferous is admirably exposed in the gorge of the Avon (Fig. 113) at Bristol. It consists of massive limestone, with shales at the base, towards the middle, and again at the top. Lithologically the following divisions have long been recognised, and their relations to the palaeontological zones are shown below.

D	=	'Millstone Grit' (sandstone). Upper Limestone Shales.
S_2	=	Middle Limestone.
C_2S_1	=	Middle Limestone Shales.
$Z + C_1$	=	Lower Limestone.
K	=	Lower Limestone Shales.

When the Lower Carboniferous is followed into South Wales certain differences appear. *Cyathaxonia* occurs at the top of D_2 while the beds above consist of radiolarian chert, followed by shales with *Posidonomya becheri*, *Glyphioceras reticulatum* and other fossils belonging to the goniatite facies.

Another interesting feature is that as the beds are traced towards the west, along the southern border of the coal-field, both the *Caninia* zones gradually disappear, and at last the *Seminula* zone rests directly upon the *Zaphrentis* zone. This is apparently due to an unconformity with accompanying overlap which, in the east, begins in the middle of the *Caninia* zones.

Midlands.—When traced northwards from Bristol the Carboniferous Limestone rapidly decreases in thickness. At first this is due mainly

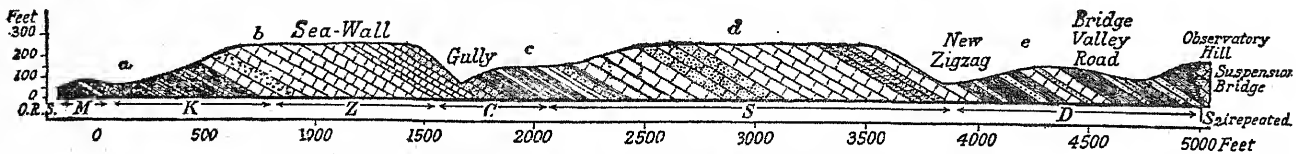


FIG. 113.—SECTION IN THE AVON GORGE. (After Dr. A. Vaughan.)

a, Lower Limestone Shales; *b*, Lower Limestone; *c*, Middle Limestone Shales; *d*, Middle Limestone; *e*, Upper Limestone Shales with Upper Limestone. The letters *M*, *K*, etc., refer to the palaeontological classification, for which see p. 360.

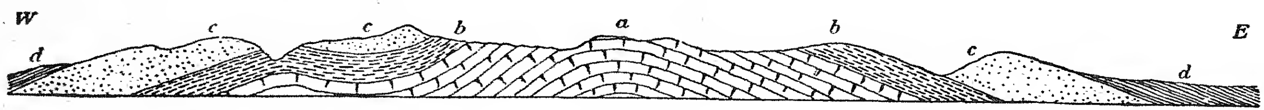


FIG. 114.—DIAGRAMMATIC SECTION ACROSS DERBYSHIRE.

a, Carboniferous Limestone; *b*, Limestone Shales; *c*, Millstone Grit; *d*, Coal Measures.

to the fact that the upper beds are replaced by arenaceous deposits. In the Forest of Dean, for example, the limestone includes only the representatives of the *Cleistopora*, *Zaphrentis*, and *Caninia* zones, with, possibly, a part of the *Seminula* zone, and it is followed immediately by the Millstone Grit of that area. There is said to be no unconformity, and hence the sandstone must represent, more or less completely, the higher part of the Bristol succession. In the Clee Hills, in Shropshire, a similar grit follows close upon the *Zaphrentis* zone, the arenaceous facies thus beginning at an even earlier date than in the Forest of Dean. Further north the Lower Carboniferous disappears entirely, and in parts of the South Staffordshire and Warwickshire coal-fields the Upper Carboniferous rests directly upon Silurian or older beds.

Derbyshire and North Wales.—But the series again thickens rapidly towards the north, and in Derbyshire (Fig. 114) it is represented by some 1,500 feet of massive limestone, with occasional bands of basaltic lava and tuff, known locally as toadstones. The beds form a broad anticline; but even in the centre of the arch the base of the series is not exposed. The whole of the visible limestone, probably, belongs to the *Dibunophyllum* zone, with the *Cyathaxonia* subzone at the top. Above the latter comes the series known as the Limestone Shales. In general there is a passage from the one to the other, but locally they are separated by an unconformity.

In North Wales the succession is very similar, except for the absence of the volcanic beds. The base, however, is well exposed. Sometimes it consists of red sandstones and conglomerates, which were formerly supposed to belong to the Old Red Sandstone; but usually the limestone rests directly upon Silurian or Ordovician beds. It is possible that a very small thickness may belong to the *Seminula* zone; but the rest, as in Derbyshire, forms the *Dibunophyllum* zone, with the *Cyathaxonia* subzone, followed by the shaly facies at the top.

Just north of the Peak district the Lower Carboniferous disappears under the Millstone Grit, and except for one or two small inliers is not seen for some 25 miles, but it reappears in strong force in the Bowland and Craven districts and from thence the outcrop is continuous to the Scottish border. In this long stretch of country the rocks show much variation of thickness and lithology. The succession is nowhere complete, the K zone being unknown at the surface in the north of England and the Z zone very feebly represented locally. The most striking feature is the great change in thickness and lithology at the line of the Craven fault-system, which though obviously largely post-Carboniferous, must have existed in some form in Lower Carboniferous times, when it controlled the sedimentation. South of the faults the series is very thick. The black Clitheroe Limestone (Z and part of C) is followed by dark cherty limestones and shales of Visean age, with *Posidonia becheri* and goniatites, and above this come the Lower

Bowland Shales, also with a goniatite-lamellibranch fauna: the zoning is based on goniatites.

An important feature of this area is the lenticular masses of shelly limestone known as *reef-knolls*. They are relics of a shell bank eroded by wave action into blocks, principally along fault-lines, and later covered by Upper Carboniferous shales. They are in fact topographical features of middle Carboniferous age now being uncovered. In Craven they occur high in the Visean, though further south reef-knolls are found at lower horizons.

North of the faults there is no equivalent of the Clitheroe Limestone. At the base of the Carboniferous is the Great Scar Limestone (600 feet), principally of S and D age, which gradually increases in thickness northwards with the incoming of intervening sandstones and shales. It extends about as far as Stainmoor: that is to say it occurs on the tectonic unit known as the Askrigg Block. Here also is the fullest development of the Yoredale beds, the equivalent of the Lower Bowland Shales and therefore of the highest Visean (D_2—D_3). These consist of a series of limestones, shales and sandstones repeated many times in rhythmic succession and forming marked step topography along the sides of the dales. It is the Great Scar Limestone that determines the characteristic features of the Ingleborough country described in Chapter IV.

Near Ravenstonedale in Westmorland lower beds come in, probably as low as Z, but northwards, on the Alston Block, they are again absent. The equivalent of the Great Scar Limestone becomes less and less calcareous and more of the Yoredale type, indicating that the Yoredales are really a facies and not a definite time division. An important feature of the Alston Block is the Whin Sill (see p. 246). North of the Alston Block, in the Bewcastle Syncline, the whole succession is again very thick and in Northumberland has been subdivided as follows:

Bernician Series	Limestone group.
	Scremerston Coal group.
Tuedian Series	Fell Sandstone group.
	Cementstone group.

In this area the local names Tuedian and Bernician are used for major subdivisions of the Lower Carboniferous, but they must not be taken as exactly equivalent to Tournaisian and Visean. Here sandstones and shales are dominant and there are workable coal-seams. The base of the system rests quite conformably on the Upper Old Red Sandstone and the boundary is rather ill-defined.

In the mining area of West Cumberland, around Whitehaven and Workington, the Lower Carboniferous rests directly on the Skiddaw Slates. It is divided into two series: the lower, about 700 feet thick, being almost entirely composed of seven limestones, numbered (unfortunately) from the top downwards. In this series lie the important

haematite deposits (see p. 283), so that the succession is known in minute detail. The upper or Hensingham division consists of shales, sandstones, grits and subsidiary limestones. The whole area is extensively faulted, as will be mentioned again when describing the Coal-measures of the district.

		Bowland Forest.	Askrigg Block.	Ravenstonedale.	Alston Block.
D	3 2 1	Bowland Shales	Yoredale Series	Yoredale Series	Yoredale Series
S	2	Pendleside Limestone	Great Scar Limestone	Snipe Scar Limestone	Melmerby Scar Limestone
	1			Ashfell Sandstone	
C	2			Ravenstonedale Limestone	
	1	Clitheroe Limestone			
Z				Basement Conglomerate	

Correlation Table of the Lower Carboniferous Rocks of Northern England.

Scotland

The Lower Carboniferous rocks come to an end about the latitude of Berwick, but reappear again in great force in the Midland valley of Scotland, where they occupy the whole central part of the great syncline, between the two parallel outcrops of Old Red Sandstone. Here they include some very large spreads of volcanic rocks, chiefly basalts. Here again there is not much limestone, as compared with the south of England, while in some regions the series is very thick. It rests conformably on the Upper Old Red Sandstone, and the junction is rather vague in some places.

The general succession is shown in the following table:

Carboniferous Limestone Series	Upper Limestone group. Lower Limestone group.
Calciferous Sandstone Series	Oil Shale group. Cementstone group.

Thus it will be seen that the Carboniferous Limestone as defined in Scotland is not the same as in England, but includes only the equivalents of the upper part of the latter. The Calciferous Sandstone series must include some of the Bristol zones. As at Bristol the lowest part of the local 'Millstone Grit' is probably Lower Carboniferous.

The Cementstone group consists of a rhythmical alternation of shales

and argillaceous dolomites with sun-cracks and ripple marks, laid down in lakes subject to occasional drying up. There are a few fresh-water fossils.

The Oil Shales of the Lothians consist of curious highly carbonaceous rocks, which have given rise to a very important industry: for an account of this see p. 184.

Locally a great part of the Calciferous Sandstone series is replaced by thick masses of lava, which built up great plateaus, (Clyde Plateau, Garlton Hills, etc.) in places 2,000–3,000 feet thick.

The lower part of the Lower Limestone group is not of much importance, as it consists mainly of shales and limestones with a few thin coals, but the upper half (the Edge Coal group of Midlothian) contains the most important coal seams of Scotland. It consists of alternating sandstones and shales, with ironstones, fireclays and coals.

The Upper Limestone group is unimportant, as it is mainly sandy, with several limestones and a few thin coals.

When looking at a small scale geological map of the region it should be noted that much of the coal production of Scotland comes from strata coloured like the Carboniferous Limestone of England, as well as from areas indicated as Coal Measures.

Besides the great basalt plateaus before mentioned the whole area is riddled with innumerable volcanic necks, sills and dykes.

Ireland

In Ireland the Lower Carboniferous extends almost unbroken from the southern coast to the shores of Lough Foyle and Belfast Lough, and shows a rather similar variation to that met with in Britain.

South of the latitude of Cork it consists of a great thickness of dark slates, mudstones and sandstones, up to 5,000 feet thick, the so-called 'Carboniferous Slate' series, which is the Irish representative of the Culm of the Armorican geosyncline. The lower part, including the Coomhola series, represents a lateral replacement of the higher beds of the O.R.S. by estuarine and marine detrital deposits of Upper Devonian age, and contains fossils of K and pre-K age (i.e. Devonian according to the Second Heerlen Congress). The upper part represents a lateral replacement of the lower beds (Tournaisian) of the Carboniferous Limestone, and contains a fauna of Z — C_1 age (possibly also C_2).

About the latitude of Cork massive grey limestones with shales below appear in a series of synclinals exposed on the Wexford and Waterford coasts. At Hook Head and Dungarvan the O.R.S. passes up into shaly and sandy beds with a K fauna; limestones become more abundant in the Z zone, and the sequence ends with reef limestones of up to S_1 age. In County Dublin there is a considerable thickness of slates, shales, conglomerates and limestones, with a good faunal sequence from K up to D_3. Beds with *Cyathaxonia* (S_2 — D_1) are well

developed and are followed by limestones and shales with *Posidonomya*.

Northwards and westwards the limestones increase in thickness up to some 3,000 feet and underlie much of the drift and bog-covered central plain of Ireland. The bare plateaus of almost horizontal limestone in Clare and Galway show a thin sandy K facies at the base following on the O.R.S., and pass up through a complete sequence to D_3. North-eastwards towards the Newry axis the limestones of Carlingford and Strangford Loughs are seen to be replaced by sandstones and shales as the old land ridge is approached.

In Co. Antrim there is an interesting area of Lower Carboniferous rocks with coal seams around Ballycastle, forming a synclinal basin lying in the region of the Dalradians and comparable to the Machrihanish Coalfield of Kintyre. Its lower portion consists of conglomerates, sandstones and shales, with coal seams and black band ironstones, ash beds and contemporaneous lavas, all of Calciferous sandstone age. Overlying the ash beds is the Carboniferous Limestone series, consisting of sandstones and grits with limestone bands, the thickest of which is of D_2 age. The field contains three seams of blackband ironstone and ten seams of bituminous and anthracitic coal, mostly thin and dirty and now worked out.

UPPER CARBONIFEROUS

Owing to folding and denudation since the Carboniferous rocks were laid down, the Upper Carboniferous now forms a number of separate basins, several of which are in part and one wholly concealed by newer deposits. For convenience of description these basins may be grouped as follows:

1. The Devon syncline.
2. The Armorican group (including the South Wales, Somerset and Gloucestershire coal-fields and the concealed coal-field of Dover).
3. The Midland group.
4. The Northern group.
5. The Scottish group.
6. The Irish group.

Throughout the British Isles the Upper Carboniferous consists chiefly of sandstones and shales, with seams of coal. The deposits are generally of fresh-water or terrestrial origin, but marine bands occur at several horizons.

Towards the base of the series sandy or gritty material usually predominates, and in some districts it forms a well-defined series, mainly sandstone, which goes by the name of the Millstone Grit. The succeeding beds are known as the Coal Measures, and are usually divided into a Lower, Middle and Upper series. In other areas, however, the basal sandstone is broken up by intercalated beds of shale, with occasional thin seams of coal, and cannot be distinguished litho-

logically from the Lower Coal Measures; nor is there any essential difference in the contained fossils. But the name is still retained, and in most of the coal-fields the Upper Carboniferous is divided into four series:

Upper Coal Measures.
Middle Coal Measures.
Lower Coal Measures.
Millstone Grit.

This simple method of classification is however quite impracticable, owing to the different meaning attached to the names in different areas. The accompanyiug table is intended to show the confusion now prevailing in the use of the terms Lower, Middle, and Upper Coal Measures in four of the principal coalfields. It will be observed that in hardly any instance do the lines coincide. It follows therefore that the only possible scientific treatment is to ignore local nomenclature and stick to fossil zones. In the past zones have mainly been founded on plants, as shown in the second column, but these are not very satisfactory owing to the long range of single species, and the classification has depended on groups. It is now found however that fresh-water lamellibranchs give much more definite results. The zones now generally adopted are set forth in the right hand column of the table. (Sometimes the *similis-pulchra* zones are combined, and then split

<table>
<tr><th>Marine Beds.</th><th>Plant Groups.</th><th>Durham.</th><th>Yorks.</th><th>North Staffs.</th><th>South Wales.</th><th>Lamellibranch Zones.</th></tr>
<tr><td rowspan="6">Anthracoceras</td><td rowspan="2">RADSTOCKIAN</td><td rowspan="2"></td><td rowspan="2">Upper</td><td rowspan="4">Upper</td><td>Upper</td><td rowspan="2">tenuis</td></tr>
<tr><td rowspan="2">Pennant</td></tr>
<tr><td rowspan="2">STAFFORDIAN</td><td rowspan="3">Upper</td><td rowspan="6">Middle</td><td rowspan="2">phillipsi</td></tr>
<tr><td rowspan="7">Lower</td></tr>
<tr><td rowspan="4">YORKIAN</td><td rowspan="5">Middle</td><td rowspan="2">pulchra</td></tr>
<tr><td rowspan="3">Middle</td></tr>
<tr><td rowspan="5">Gastrioceras</td><td>similis</td></tr>
<tr><td>modiolaris</td></tr>
<tr><td rowspan="3">LANARKIAN</td><td rowspan="2">Lower</td><td rowspan="3">Lower</td><td rowspan="2">ovalis</td></tr>
<tr><td rowspan="2">Lower</td></tr>
<tr><td>"Millstone Grit"</td><td>"Millstone Grit"</td><td>lenisulcata</td></tr>
</table>

into Upper and Lower: this does not seem to possess any advantages over the simpler arrangement shown.) To save space in the table only

the specific names of the zone-fossils are given, following the common practice: the full names are as follows:

Anthracomya lenisulcata; Carbonicola ovalis; Anthracomya modiolaris; Anthracomya pulchra; Carbonicola similis; Anthraconauta phillipsi; Anthraconauta tenuis.

It will be noted that in two of these areas part of the "Millstone Grit," contains fossils of a Coal Measure zone.

The Millstone Grit is now zoned by goniatites, as will be discussed later, and this group also occurs in some of the marine bands in the Coal Measures: *Gastrioceras* is the dominant genus in the lower measures and *Anthracoceras* in the higher.

Besides these forms, remains of fish are also abundant, and several genera of amphibians have been found. Insects, spiders, etc., also occur; and in some beds Entomostraca are found in swarms.

All these forms occur in the normal deposits which constitute the greater part of the series. But at various horizons throughout the series there are bands of rock with a totally distinct fauna, which evidently lived in the sea. Cephalopods and lamellibranchs are the commonest forms, but gastropods and brachiopods also occur in considerable numbers.

Classification of the Upper Carboniferous.—The table just given shows that it is impossible to use the common local terms Lower, Middle and Upper Coal Measures in any consistent sense in different areas. Nearly everywhere in Britain a distinction is drawn between the Millstone Grit and the Coal Measures, though even this cannot always be carried out on any strictly scientific lines. Hence in the following descriptions of individual areas, each will be treated on its own merits, by reference to palaeontological divisions, without any attempt to fit them all into a general classification. With reference to the grouping by plants, it may be noted that instead of Yorkian, the name Westphalian is sometimes used, but this is inadvisable, since on the Continent Westphalian includes everything from the base of the Millstone Grit to the top of the Red Beds of North Staffordshire, as measured by zones. But the name Yorkian is not satisfactory, as it suggests a reference not to the county but to the city of York, which does not stand upon Coal Measures. An entirely new name is needed. Some continental geologists employ the name Namurian for the approximate equivalent of the British Millstone Grit, which others include in the Westphalian, as stated above.

Lithology of the Upper Carboniferous.—The character of the Millstone Grit strata will be described later. The Coal Measures are very uniform in most areas: all the lower divisions are very similar, and it is only in the highest that red beds make their appearance, indicating the oncoming of arid conditions. All the rest are, broadly speaking, swamp and delta deposits varied by occasional incursions of the sea, indicating

a slow but not uniform depression. By far the commonest rock-type is grey shale or mudstone with an occasional sandstone, varied by nodules or beds of clay-ironstone and coal-seams, usually with a seat-earth or fireclay below, sometimes a bed of ganister (see p. 164). The marine bands consist of shale or black limestone, often crowded with fossils and there are also beds with fresh-water lamellibranchs, which have proved so useful in zoning. The plant remains are found in the shales, often in the roof of the coal-seams. For an account of the origin and varieties of coal see p. 180.

There is a big break in the floral sequence in Britain and North-western Europe between the Lower and Upper Carboniferous floras, located somewhere in the goniatite zone H, and not at the base of the Upper Carboniferous in the usual sense, as originally thought by Kidston. With one or two possible exceptions no species is known to cross this boundary.

Algae in the Upper Carboniferous were mainly concerned in the formation of boghead coals. Bryophyta (Mosses and Liverworts), once thought to be a modern group, have been found to be represented. Pteridosperms are very abundant and reach their maximum in the Upper Carboniferous and form a dominant part of the vegetation. Some of them like *Lyginopteris*, were like tree-ferns in habit, whereas others were much humbler plants resembling the filmy ferns. This morphological resemblance to ferns misled earlier investigators, but it has been known for some years now that they differ in the possession of seeds and the power to form secondary wood. They are identified on the basis of the shape and venation of the leaflets, and on the structure of the fertile fronds where these are recognizable. The commonest genera are *Pecopteris*, *Alethopteris*, *Callipteris*, *Mariopteris*, *Neuropteris*, *Linopteris* and *Lyginopteris*.

The Articulatae are represented principally by *Calamites* (now subdivided into Eucalamites, with many branches, and Stylocalamites, with few branches) with *Annularia* and *Asterophyllites* (leaves) and *Calamostachys* (cones). Also abundant is *Sphenophyllum*, a rather distinct Articulate type.

The Lycopodiales are represented by many different forms of *Lepidodendron*, *Sigillaria*, *Bothrodendron* and other genera, which attained the stature of large trees, and contributed very largely to the formation of our coal seams, the spores alone often being important coal formers. In the rocks below the coal their roots, known as *Stigmaria*, are found.

True ferns are not as common as was once thought; they include genera such as *Psaronius*, *Asterotheca*, *Botryopteris*, *Metaclepsydropsis* and *Botryoxylon*, and are not easily separable from the Pteridosperms, as already mentioned, unless the reproductive organs are present.

The main Gymnosperm groups are fairly well represented by the close of the Upper Carboniferous. *Cordaites* is common, also early

Cycadophytes such as *Dioonites* and *Pterophyllum.* The Ginkgoales may be represented by *Psygmophyllum*; and *Walchia, Dicranophyllum* and others represent the rising group of Conifers. Gymnospermous seeds such as *Trigonocarpus* are not easily assigned to their parent stems.

Local Variations in the Upper Carboniferous

Devon.—In the centre of the great Devon syncline a large area is occupied by Upper Carboniferous rocks of a special facies, consisting of dark grey and greenish shales with sandstones and grit bands and a few thin limestones. Here and there are beds of a soft coal, locally known as *culm.* There is a close resemblance to rocks of similar age in Germany, where the term Culm Facies is extensively used. Fossil plants and goniatites show a general resemblance to those of the lower part of the normal sequence; Lanarkian and perhaps part of the Yorkian. The lowest beds with indefinite plants of no zonal value, such as *Calamites*, may perhaps represent the Millstone Grit.

The Armorican Group.—Through the Mendip Hills and the southern promontories of Wales there runs a zone of intense folding, which may be traced westwards into the south of Ireland and eastwards into Belgium and beyond. The trend of the folds is approximately from west to east, and they were produced at the close of the Carboniferous period. They form the outer zone of a great system of mountains which at that time was raised across the middle of Europe, but of which only fragments now appear from beneath the later deposits. It is a branch of the Hercynian system of Bertrand, and was the most prominent feature in the geography of Europe at the close of the Palaeozoic era.

Immediately to the north of this range, and in part involved within its folds, lies a series of coal-fields. In Ireland there are the Munster and Leinster coal-fields; in Britain, the coal-fields of South Wales, the Forest of Dean, Bristol and Radstock, and also the hidden coal-field of Dover; in Belgium and the north of France, a long and narrow band, the greater part of which lies buried beneath later beds; in Germany, the coal-field of the Ruhr.

The edge of the folded zone is often thrust over the coal-basin in front of it; and in the process the southern rim of the basin has been so extraordinarily crumpled that a vertical shaft may pass through the same coal-seam five times in succession. This is very clearly seen in Belgium, where the folded Devonian and Lower Carboniferous rocks of the Ardennes have been pushed over the coal-field of Namur and Liége. In England the Mendip Hills correspond with the massif of the Ardennes, and as the Mendips are approached from the north, the same crumpling and overfolding of the coal-seams is observed, and the Carboniferous Limestone masses of Vobster and Luckington have been thrust over the Radstock coal-field.

In the South Wales coal-field the Millstone Grit ends with a massive sandstone called the Farewell Rock, and the Coal Measures are divided into an upper and a lower productive series, separated by an intervening series of sandstones in which coal-seams are less numerous. The beds may therefore be grouped as follows:

Upper series, with coal-seams.
Middle or Pennant Sandstone series (with workable seams west of the Taff).
Lower series, with coal-seams.
Millstone Grit.

In South Wales the coals, which are bituminous in the east, gradually lose their volatile constituents towards the west, and are converted into anthracite. This is true especially of the lower division, and this division yields most of the steam-coal for which South Wales is famous.

In the Bristol and Somerset coal-fields the Millstone Grit belongs in part to the Lower Carboniferous: in the Forest of Dean it begins in the *Seminula* zone. In both areas there is an arenaceous development in the middle of the Coal Measures, as in South Wales, the Pennant group, but not always at the same horizon. In the Forest of Dean all the Coal Measures are Staffordian and Radstockian. The Bristol succession is much as in South Wales, but there is no coal of Lanarkian age: this division seems to be represented by part of the Millstone Grit in the local sense. In the southern half of the field, around Radstock, the structure is very complicated and there are inversions and overthrusts. This is the only area in Britain where there are workable coal seams in the highest, Radstockian, division.

In the concealed Dover coal-field the top of the Coal Measures is at an average depth of something like 1,000 feet below the surface. Numerous deep bores and shafts have revealed a basin of Coal Measures thickest in the middle (2,800 feet) and thinning out on all sides. There are about 29 coal seams, some up to 9 feet thick. The measures belong to the upper zones (*phillipsi*, etc.).

Midland Area.—In the Midlands there is a small group of coal-fields where the Lower Carboniferous is absent and the Upper Carboniferous rests directly on an old land surface. This group includes the coal-fields of South Staffordshire, Warwickshire and Leicestershire and small strips resting against the old rocks of the Welsh Borderland. Over a large part of this area the Coal Measures are concealed by New Red Sandstone beds, and some of the Coal Measures extend below the surface well beyond their visible outcrops. One of the characteristic features of this area is the development of red barren measures in the upper division, many of which were once believed to be Permian. The last 'Permian' outcrops of the Midlands have disappeared from the latest official maps. It is unnecessary to give details of all of these fields, as the type area for the red beds is in the North Staffordshire

coalfield which belongs to the next group. In one part of the Warwickshire field between Nuneaton and Coventry five coal seams, separate further north, run together into one great seam over 20 feet thick, by thinning out of the intervening strata, and in South Staffordshire seven seams behave in a similar way forming a seam with a maximum thickness of 30 feet.

Northern England.—North of a line drawn east and west through Nottingham is a group of great coal-fields of first class importance. These are: Yorkshire, Nottinghamshire and Derbyshire; Durham and Northumberland on the east of the Pennines, and North Staffordshire; Lancashire; and Cumberland on the west, with a smaller one in the north-east corner of Wales (Flint and Denbigh). This last is probably continuous with that of North Stafford, though at a great depth, under the Cheshire plain, and both possibly with Lancashire.

North Staffordshire.—The table on p. 368 shows that all the divisions of the Coal Measures are here represented to their fullest extent. The Millstone Grit is much the same in lithology in all these northern areas, though varying very greatly in thickness. A general description of it may well be deferred till the type area is dealt with, namely, the Pennine Hills between Yorkshire and Lancashire, where it reaches its fullest development.

The real interest of the North Staffordshire or Potteries coal-field lies in the type development of the highest part of the series, which may be broadly called the Red Beds, although they are not all red. These are in the *tenuis* and most of the *phillipsi* zones of the table on p. 368. The local subdivisions, which are also applicable to some of the Midland coal-fields of the last section, are

Keele group.
Newcastle group.
Etruria Marl group.
Black Band group.

Of these only the Keele beds are in the *tenuis* zone; the rest are *phillipsi*. The Black Band group includes a few thin coal-seams and beds of ironstone, one of the few examples of Coal Measure ironstones actually worked in recent times.

The Etruria Marls are purple, red or mottled clay-like beds, with occasional bands or lenticles of grit or fine conglomerate, locally known as 'espleys.' The marly beds are very largely worked for the manufacture of the coarser and more massive forms of Staffordshire ware, such as sanitary bricks and pipes.

The Newcastle group, whose equivalent near Birmingham is called the Halesowen group, consists mainly of grey shales and sandstones with a few thin coals of no importance.

The Keele beds belonging to the *tenuis* zone and therefore of Radstockian age, are represented in all the Midland coal-fields. They

consist mainly of red and purple sandstones and bright red marls and clays, with several thin beds of *Spirorbis* limestone, which are useful for correlation with other areas.

The productive measures of the Potteries coal-field, though including many important seams, are quite normal and show nothing of particular geological interest.

A glance at a geological map of England will show that the N.–S. Pennine axis and the E.–W. Howgill-Cleveland axis form a cross of pre-Coal Measure rocks. Between the arms of the cross lie great coal-fields or groups of coal-fields, thus: S.E., Yorks, Derby, Notts; N.E., Durham and Northumberland; S.W., N. Staffs and Lancashire; and N.W., the Cumberland coal-field, which has been largely destroyed by the later, perhaps Tertiary uplift of the Lake District dome. The south-eastern and south-western quadrants are partly covered by New Red Sandstone rocks and the continuation of the north-eastern and north-western quadrants lies under the sea. At the present time a very large production of coal comes from the concealed part of the Yorks-Derby-Notts field, especially around Doncaster, under the New Red strata.

One of the most notable features of the northern coal-fields is the occurrence of occasional bands containing marine fossils among the ordinary deltaic beds. Some of these have a very wide extension, so much so that it has been found possible to correlate them, and therefore the coal-seams between them, across the southern Pennines, and it is found that the succession in these areas is very similar. The striking changes in Upper Carboniferous rocks are from north to south, not from east to west.

In this area also the Millstone Grit reaches its greatest and most typical development. In the south it appears to be completely conformable to the Lower Carboniferous, but in North-west Yorkshire it rests with overlap on the denuded edges of the Yoredale series. The formation is thickest in north Derbyshire, where it forms the characteristic scenery of the Peak district.

The Millstone Grit is a series of alternating shales, sandstones and grits, the latter often very coarse and pebbly. It is marked by abundance of felspar in the grits, which when decomposed gives a characteristic appearance easily recognised. All the thick grits have individual names, the two most important being the Kinderscout Grit near the middle and the Rough Rock at the top, which has a very wide extension. The grits always form the most prominent features of the scenery, especially the great 'edges' or escarpments, but actually there is a high proportion of shales, which of course are not conspicuous.

There has in the past been a good deal of confusion as to the correlation of parts of what are now defined as the Millstone Grit—for example, in Derbyshire the lower part was supposed to be equivalent

to the Yoredales, but the modern study of goniatite zones has cleared the matter up. The major zones, with their index letters, are as below:

G. *Gastrioceras* zone.
R. *Reticuloceras* zone.
H. *Homoceras* zone.
E. *Eumorphoceras* zone.

These major zones are divided into many sub-zones, which need not be enumerated here. The goniatites occur in occasional marine bands, much as in the Coal Measures. In many places there are thin coals and seat-earths, which become more important northwards. In the southern Pennines the maximum thickness of the whole series is about 3,000 feet; in Durham perhaps only one-tenth of this.

In Yorkshire and Lancashire the base of the Coal Measures rests quite conformably on the Millstone Grit, and coal-seams are very numerous in the lower and middle part, Lanarkian to Staffordian, but in Yorkshire the highest division is only feebly represented by a little red marl in the *tenuis* zone: in Lancashire this division is rather thicker. In Durham the *lenisulcata* zone is part of the local Millstone Grit, while the highest beds present are Staffordian, so that the 'Upper Coal Measures' of Durham are entirely below the similarly named group in Yorkshire. The coal in the exposed areas in Yorkshire is largely worked out and a great part of the production comes from deep pits penetrating the New Red Sandstone. Coal Measures have been found in bores even east of the Trent and the hidden coal-field possibly extends as far east as the neighbourhood of Lincoln.

Every individual seam has a name, and most of them several names, in different areas. In the eastern field one of the most important is the Barnsley or Top Hard, the basal member of the *similis* zone, which in the economic literature is commonly used as a datum line in discussions of the depth and distribution of other seams. The Mansfield Marine Bed is at the top of the *pulchra* zone.

The coal-field of West Cumberland is probably only a relic of a once much larger basin which has been uplifted and removed by denudation over the site of the Lake District. Some of the seams are worked for over three miles under the sea near Whitehaven. The productive measures are mainly in the Yorkian group, while the higher beds are represented by the unconformable purple or reddish Whitehaven Sandstone. This field is considerably disturbed by a system of N.W.–S.E. faults, some of which have a much greater throw in the Carboniferous than in the overlying New Red Sandstone, indicating two distinct periods of movement.

Scotland.—In the Midland Valley of Scotland, as before noted, only a part and probably not the most important part of the coal production comes from the equivalent of the English Coal Measures. The Upper

Carboniferous coals come from the *similis-pulchra* zones, while the higher zones comprise barren red measures.

It is probable that many of the sills, dykes and volcanic necks, so abundant in the Midland Valley were intruded during the Upper Carboniferous, but such activity certainly continued locally into New Red Sandstone times, so that it is not always easy to fix their exact ages. It now appears that the Scottish Carboniferous igneous rocks, both extrusive and intrusive, include such an endless diversity of types that it is impossible to discuss them here. For an account of them reference should be made to a textbook of petrology.

Ireland.—Upper Carboniferous rocks are confined to comparatively small areas that remain as relics of a great tract of Coal Measures now mostly lost to us by denudation. In the south there is a large area in Clare, Limerick and Kerry ; a smaller but commercially more important basin in Leinster, north of Kilkenny ; and several still smaller patches. The succession in general is not unlike that of the Midland coal-fields of England, except that the Upper Coal Measures (Staffordian-Radstockian) are absent. The Leinster coal-field forms a roughly oval-shaped plateau, rising abruptly from the limestone plain, with a marked central depression, and is a basin both in geological structure and topographic form. The sequence is:

4. 'Middle Coal Measures': shales, etc., with productive coal seams, now mostly worked out.
3. 'Lower Coal Measures': shales and sandstones with 4 important coal-seams, and a number of marine bands containing *Gastrioceras listeri* and *Dimorphoceras gilbertsoni*. Lamellibranchs of the *modiolaris* zone also occur, suggesting a Yorkian age, though the precise correlation of this and the Middle Coal Measures has not yet been determined.
2. Flagstone ['Millstone Grit'] series: flags and massive sandstones, with shales. Probably the equivalent of the 'Millstone Grit' of the Midlands (i.e. Namurian).
1. Black shale series: black shales, followed by grits and mudstones, with *Goniatites, Aviculopecten, Posidonomya,* etc. Probably Upper Visean in age.

In the north of Ireland there are several small basins, in Co. Leitrim and Co. Tyrone. That of Dungannon, Co. Tyrone, is the most important coal-field in Ireland, though only 5 square miles in area. It possesses excellent fireclays and 24 bituminous coals of a total thickness of about 60 feet, the thickest being 9 feet.

From recent detailed studies of the distribution of important coal-seams in Great Britain one fact has clearly emerged, namely, that there was not, as formerly supposed, a continuous migration of maximum coal formation southwards, from the Lower Carboniferous in Scotland, through the middle of the system in northern England to the higher divisions in the south. On the contrary, the Lower Carboniferous

coal-formation in Scotland was an isolated episode, which came to an end, and the greatest concentration of workable coal-seams everywhere took place about the horizon of the *similis* and *modiolaris* zones, or as expressed in palaeobotanical divisions, mainly in Yorkian times, which is equivalent broadly to the Middle Coal Measures of most of the principal fields. This must have been a period of strangely uniform conditions over a very large area. In several fields this period of coal formation on a large scale ended more or less in an incursion of the sea marked by a conspicuous marine band known east of the Pennines as the Mansfield Marine Bed, whose equivalent has been traced in other areas on fossil evidence. Above this bed in several fields the number of workable seams is small.

CHAPTER XXI

THE NEW RED SANDSTONE SYSTEM

The strata described in this chapter have hitherto been divided by all modern geologists into two separate systems, the Permian and the Trias, but it is difficult to see why, and still more difficult is it to explain the drawing of the dividing line of the Palaeozoic and Mesozoic groups between them. In many parts of the world the strata from the Carboniferous to the Jurassic belong to one period of continuous undisturbed sedimentation. There was, however, in Britain in latest Carboniferous times an orogenic disturbance of the first magnitude, the Armorican or Hercynian revolution, so that there is a violent unconformity between the Coal Measures and the Permian, which makes a good dividing line, though this was not adopted.

In the early days of stratigraphy the strata in question were grouped together as the New Red Sandstone, a highly appropriate name, and this is here revived. As compared with the usual practice, then, the classification is as follows:

New Red Sandstone System.	Trias	Rhaetic Series.
		Keuper Series.
		Bunter Series.
	Permian	Magnesian Limestone Series.
		Marl Slate Series.
		Lower Sand Series.

But recent research has shown the probability that in some areas part of the Magnesian Limestone is equivalent to part of the Bunter as formerly defined in other areas. For several reasons also the Rhaetic would fit in better with the Jurassic System, as it is a marine formation, marking the beginning of the next marine period (see Chapter XXVII).

As before mentioned the close of the Carboniferous period was characterised, not only in England but also over a large part of Europe, by extensive movements of the earth's crust. The most violent crumpling took place along a broad zone stretching from west to east, and resulted in the elevation of the great Hercynian mountain system already described.[1] But the movements were not confined to the zone of crump-

[1] In accordance with the most modern practice the term Hercynian is taken to include the whole mountain system; the western branch, from central France to Ireland, is called Armorican, from the ancient name of Brittany, while the eastern branch from central France into western Germany is called Variscan. British stratigraphy is not concerned with the last-named.

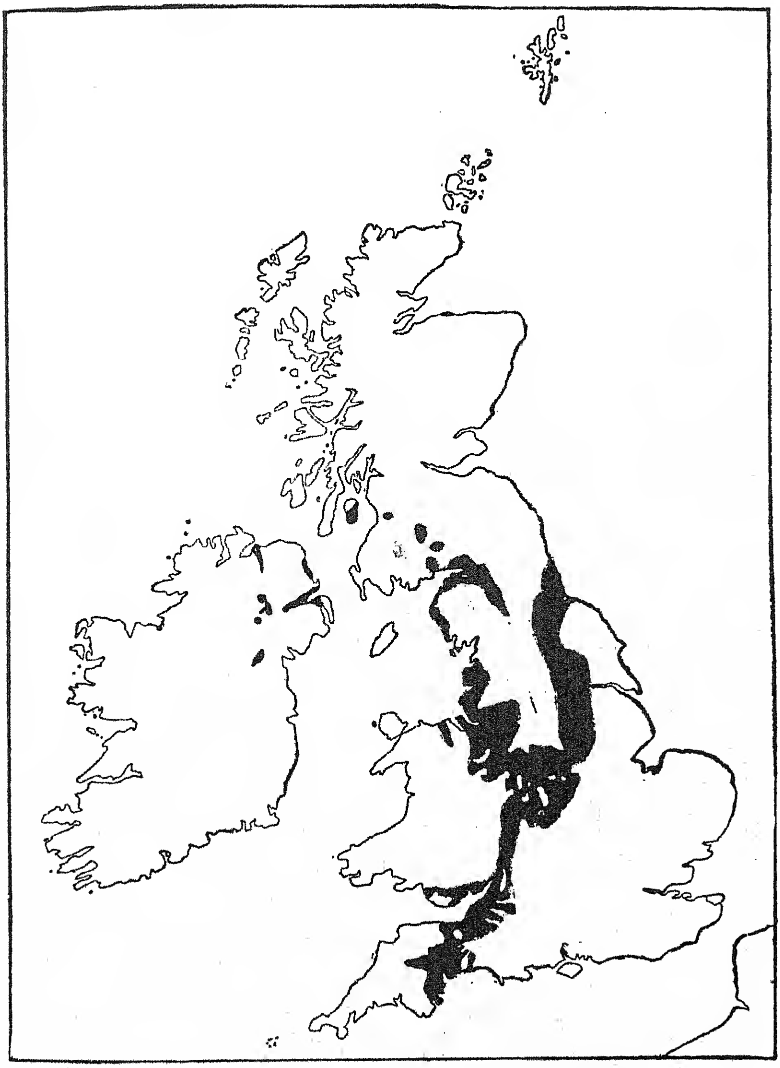


FIG. 115.—THE NEW RED SANDSTONE SYSTEM.

ling. Outside the Hercynian range the Carboniferous beds were thrown into broad anticlines and synclines, sometimes accompanied by faults of great magnitude. It is to these that the separation of the British coal-basins is chiefly due.

The folding took place before the next beds were laid down; and not only were the folds completed, but they were also denuded to so great an extent that the Lower Carboniferous rocks were exposed. Upon the irregular floor thus produced the New Red strata were deposited, and they rest unconformably upon the Coal Measures, the Millstone Grit, the Lower Carboniferous and sometimes on still older rocks.

After the deposition of the Coal Measures there must, therefore, have been a considerable interval of time, during which the greater part of Northern Europe was land. But the south and east of Europe and Central Asia were covered by the sea, for in those regions there is a continuous succession of marine deposits from the Carboniferous upwards.

The conditions were somewhat similar to those of the Devonian period. There was a continent in the north and west of Europe, while the sea spread over the south and east. But the land extended further to the south than in Devonian times.

The New Red Sandstone deposits of Northern Europe were laid down upon the continent, mainly upon the surface of the land itself, partly in landlocked seas which resembled the present Caspian and Sea of Aral. In these seas dwelt an impoverished fauna originally derived from the waters of the Carboniferous ocean.

The conditions prevailing in North-western Europe were therefore unfavourable to life and most of the Carboniferous genera became extinct, so that in places there are no fossils, while the only area where they occur in any large number is in the lower part of the series in north-eastern England, where they are of a special type, and are best described separately. Over the rest of the country, except in the Rhaetic, the fauna and flora are very limited, and the only important fossils are reptiles. The most important of these are found in the Elgin Sandstones of north-east Scotland. There has been no attempt to zone the New Red Sandstone in Britain.

It will be convenient therefore to deal here only with the fossils of the upper division, the Trias, as the rest of the system is either unfossiliferous or of the special type mentioned above.

The fauna of the English New Red Sandstone is very limited and gives a very imperfect idea of the life of the period. Nor is the flora much more completely represented, for it is only here and there that plants are found in any abundance. The Lycopods, Equisetaceae and the fern-like forms of the Coal Measures were not yet extinct, and a few of the Palaeozoic genera still survived; but the most important groups

of plants were the Conifers, e.g. *Voltzia*, and the Cycads, of which *Pterophyllum* is the commonest form.

An interesting Bryophyte flora, including such genera as *Naiadita* and *Hepaticites*, has recently been described from the Rhaetic.

Corals, echinoderms, brachiopods and molluscs, which are in general inhabitants of the sea, are naturally rare. A few lamellibranchs of doubtful affinities have been found in the Keuper. But it is only in the Rhaetic beds that marine forms occur in any abundance. The lamellibranchs *Pteria* (*Avicula*) *contorta*, *Pecten valoniensis* and *Protocardia rhaetica* are here the most important forms. The small Crustacean *Estheria minuta* occurs in crowds upon the surface of some of the Keuper shales. It belongs to the order Branchiopoda, and its living allies dwell in terrestrial waters, either fresh or brackish or salt, but not in the open sea. Remains of scorpions have been found. Many genera of fish are found, but seldom in abundance. The most interesting form is *Ceratodus*, the teeth of which are common in the Rhaetic bone-bed. They are very similar to those of the Australian mud-fish of the present day, which is indeed referred to the same genus. The amphibians are represented by the labyrinthodonts. Their footprints, curiously like the imprint of a human hand, are not uncommon on the fine shales of the Keuper series. Remains of reptiles are occasionally abundant, but their distribution is singularly local. In Great Britain the most prolific locality is the neighbourhood of Elgin, where many genera have been found, including *Hyperodapedon*, *Gordonia*, *Elginia*, etc. The earliest mammals yet discovered belong to this period. The teeth of a small form named *Microlestes* occur in the English Rhaetic. Two or three other genera referred to the Mammalia have been found in the Trias of Germany, South Africa and the United States. Some of these, however, are doubtful, and may belong to the Reptilia.

For the marine fauna of the period, it is necessary to go abroad. In the German Muschelkalk, marine fossils are often very abundant, but the number of species is not large. The lamellibranch *Myophoria* is one of the commonest forms. The crinoid *Encrinus liliiformis* and the cephalopod *Ceratites nodosus* are also characteristic.

It is, however, in the region of the Alps and Mediterranean that the marine facies of the Trias attains its fullest development. Here it consists very largely of massive limestones, often dolomitic, which are magnificently displayed in the Dolomites of Tirol. Some of these limestones are made up chiefly of calcareous algae, such as *Gyroporella* and *Diplopora*, but other marine forms are also very abundant. Brachiopods no longer maintain the dominant position which they assume in so many of the Palaeozoic limestones, and to a large extent their place is taken by lamellibranchs. Gastropods also are very abundant. Of the cephalopods, the nautiloid genera appear to be dying out, while the ammonoid forms are developing and have already

become of considerable importance. The most characteristic of the ammonoid genera are *Ceratites* and *Trachyceras*.

The most notable characteristic of the New Red Sandstone system in Britain is that, except in the Rhaetic, there are no normal marine fossiliferous deposits and in many parts of the system no fossils at all, so that the usual methods of correlation can only be applied with difficulty. As will appear later, the Magnesian Limestone is a marine formation of a sort, but it is not normal. The Bunter and Keuper are entirely terrestrial and conspicuously of the arid facies, with salt deposits, and some salt is also found in the lower beds.

New Red Sandstone strata form quite a large fraction of the surface of England, with a few small outliers in Wales, Scotland and Ireland. The general plan of the outcrop is Y-shaped, with its stem based on the coast of Devon, where there is a considerable spread, running up into Somerset. In the lower part of the Severn valley the outcrop is very narrow, but it spreads out widely over the northern Midlands, as far as the south end of the Pennine hill system. This divides it into two, the eastern branch running due north to the mouth of the Tyne, the other forming a wide spread over Cheshire and south Lancashire, with an interruption at Morecambe Bay. North of this there is a considerable outcrop in the valley of the Eden and round the north side of the Lake District. The position of some small patches in Scotland and north-east Ireland need not here be given in detail.

It has already been mentioned that a number of small outcrops of red rocks in the Midlands, till recently mapped as Permian, are now known to be of Upper Carboniferous age. Nearly all outcrops of New Red strata form comparatively low and flat country: there are no mountains of New Red rocks, while there are some notable plains, for example Cheshire and the Vale of York.

Devonshire

The red cliffs of the New Red Sandstone form a conspicuous feature of the coast scenery of Devon from a little south of Torquay to the eastern boundary of the county. In this area the former division into Permian and Trias has always broken down, as there is no visible stratigraphical break and no change of facies, except of course at the base of the Rhaetic, which is only about 40 feet from the top. In the following descriptions the Rhaetic will be usually ignored, and described later in a separate section, as it is quite unlike all the rest of the system. In Devon the lower part of the system consists of bright red sandstones, breccias and marls, with a bed of clay at the base near Torquay. There is a small development of lavas near Exeter. The total thickness is very doubtful, as much of the succession is violently current-bedded, giving a deceptive appearance of an enormously thick series all dipping steeply eastwards (railway embankment structure) and the base is only

seen in the western part of the area, where it rests on older rocks. There are no fossils.

East of the mouth of the Exe there is more lithological variety and the true bedding can be made out, so that thicknesses are determinable. The usual grouping in this area is as follows:

Rhaetic.	
Keuper . . .	Red marl with gypsum. Red and white sandstones with beds of marl; a calcareous breccia at the base.
Bunter . . .	Red sandstones. Conglomerate or pebble-beds.

The succession is similar to that of the Midland counties excepting for the absence of any Lower Bunter Sandstone.

The most interesting of the deposits are the pebble-beds, which are well exposed at Budleigh Salterton. They consist of well-rounded pebbles of quartzite and grit in a red sandy matrix. Some of the pebbles contain Devonian fossils, and may have been derived from the rocks of Devonshire. Others are Ordovician grits closely resembling those of Brittany and Veryan Bay. The size of the pebbles diminishes towards the north; and it appears probable, therefore, that they have been derived from the old Armorican range of which Brittany is one of the surviving fragments.

The finer material points to a similar source. Amongst the grains are fragments of tourmaline, staurolite, fluorspar, etc. Some of these, such as the tourmaline and fluorspar, might readily have come from the neighbouring rocks of Devon and Cornwall, but staurolite is there unknown. Moreover, the staurolite, which forms 20 per cent. of the heavy grains near Budleigh Salterton, diminishes in quantity towards the north. From an examination of the distribution of these and other minerals, it has been concluded that the main current which brought the materials of the Pebble-bed came from the south, but was enforced by tributaries from the west.

Inland to the north the lower beds form a long tongue in the trough of the great Devon syncline as far west as Crediton, but they are soon overlapped by the Bunter and succeeding divisions which cover a large area around Taunton; round the Mendip Hills; and as far north as Bristol. Moreover, the Bunter is again overlapped by the Keuper, so that most of this area consists only of Keuper Marls, with Rhaetic above. One of the most interesting beds is the so-called Dolomitic Conglomerate of the Mendips, which consists largely of boulders of Carboniferous Limestone in a dolomitic matrix, formed by the concentrated saline waters of the period. It represents boulder gravels and screes round the ancient Mendip mountain chain, which was by that time much worn down by denudation.

As before remarked the outcrop, consisting only of the upper members of the system owing to overlap, is very narrow in the lower Severn Valley, but the Rhaetic is well seen near Cardiff, as will be shown later.

THE MIDLAND DISTRICT

In the Midland district the system is subdivided as follows (see Fig. 116), the Permian being absent altogether.

Rhaetic Series.	
Keuper	Keuper Marls. Keuper Sandstone.
Bunter	Upper Variegated Sandstone. Conglomerate or Pebble-beds. Lower Variegated Sandstone.

On the whole, the deposits become finer towards the top. The Bunter consists of conglomerates and sandstones, the Keuper of sandstones and marls, and the Rhaetic chiefly of marls and shales.

The deposits are thickest towards the north-west, where the entire series is present; but towards the south and south-east the lower beds die out one after the other until in the southern part of Charnwood Forest the Keuper marls form the base of the system. The following are the thicknesses in different areas:

	Central Cheshire.	West and South sides of South Stafford Coal-field.	East Side of South Stafford Coal-field.	East Warwick.	Charnwood Forest, etc.
	Feet.	Feet.	Feet.	Feet.	Feet.
Keuper Marls . .	3000	1000	700	600	600–0
Keuper Sandstone	450	400–300	200	150	absent
Upper Variegated Sandstone . .	500	300	300–250	absent	absent
Pebble-beds . .	750–500	300		absent	absent
Lower Variegated Sandstone . .	500–200	300–0	absent	absent	absent

Moreover, deep borings have shown that no part of the Trias extends very far beneath the later Mesozoic beds; and it is clear that in this direction the Palaeozoic rocks must have formed a barrier which limited the Midland area of deposition on the south and east. As the basin to the north was gradually filled up, the higher beds spread beyond the lower and overlapped them on to the slopes of this ancient ridge.

The Keuper sandstone and the Bunter pebble-beds are harder than the rest of the formation, and their outcrops often form low lines of hills, sometimes with a steeply scarped face, which usually looks towards the north-west.

The Lower Variegated Sandstone of the Bunter series is usually reddish brown in colour, but varies from yellow through brown to vermilion. It is remarkably false-bedded, but is always a sandstone and always free from pebbles.

The **Pebble-beds** of the Middle Bunter consist in general of a mass of well-rounded pebbles varying in diameter from one inch to eight or nine. The majority are yellow or brown quartzites; but pebbles of sandstone, limestone and volcanic rock occur. Their origin is uncertain.

The **Upper Variegated Sandstone** is very like the lower sandstone. It is generally fine in grain, and usually bright red in colour, with bands and blotches of white or yellow. In some parts of the area there are occasional beds of pebbles and angular fragments.

The **Lower Keuper** is usually in three divisions. The basement consists of coarse sandstone or calcareous breccia, with cornstones and occasional beds of marl. The middle division is a fine-grained sandstone, which often yields an excellent building-stone. The upper division consists of brownish red laminated sandstones and sandy marls, known locally as 'water-stones,' a name derived from the fact that they form the source of many springs, and in borings commonly give a good supply of excellent water.

The **Upper Keuper**, or Keuper Marl, covers a larger area than any of the other subdivisions. It consists chiefly of bright red marls and shales, with occasional bands of greyish sandy and micaceous shales. Beds of gypsum occur in many places, and in Cheshire and near Worcester there are important beds of rock-salt. Towards the

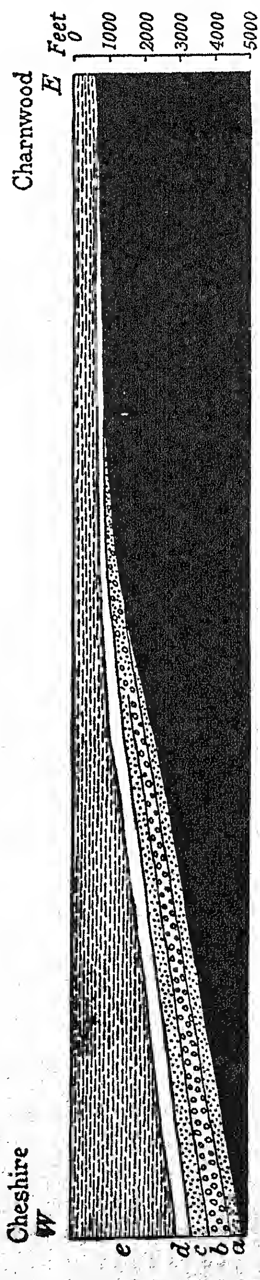


Fig. 116.—Diagram showing the Divisions of the Trias overlapping in Succession on to the pre-Triassic Floor.
a, Lower Bunter Sandstone; *b*, Bunter Pebble-bed; *c*, Upper Bunter Sandstone; *d*, Keuper Sandstone; *e*, Keuper Marls.

Jurassic outcrop a thin grey sandstone group comes in near the top of the series, but is not invariably found. In this sandstone remains of fish (*Palaeoniscus superstes*), the Crustacean *Estheria minuta* and a few lamellibranchs have been found; but the marls above and below are barren of fossils.

In the east of the district, in Charnwood Forest, the Keuper marls spread beyond the lower members of the system and rest directly upon an irregular and hilly surface of Precambrian rocks. The Precambrian outcrops of the forest are in fact only the summits of a group of hills for the most part buried beneath the Trias, and the valleys are filled with Keuper marl. Here there is clear evidence of wind-erosion. The surface of the old rocks is fresh and undecomposed, and is often smoothed and polished as if by wind-blown sand. The faces of the buried cliffs are fluted and undercut as in a desert region, and against them are banked the Keuper marls.

North-eastern District

From the neighbourhood of Nottingham, as far northward as the mouth of the Tyne, rocks of the lower division of the New Red Sandstone reappear in great force in a special facies of inland-sea type, the basin of deposition having been very much like the present Caspian, which is usually described as fresh water, though the southern end of it is very salt. The general sequence is as follows:

Trias . . .	Rhaetic. Keuper. Bunter.
Permian . . .	Magnesian Limestone. Marl Slate. Lower Sands and Breccias.

The Lower Sands consist of loose-running sands always full of water, which causes much trouble in shaft-sinking, when recourse has often to be had to freezing processes. They are very inconstant, absent in places and at the most 150 feet thick.

The Marl Slate, a shaly rock about 15 feet thick, is often rich in plant remains, such as *Ullmania*, *Alethopteris* and *Sphenopteris*, survivals from the Carboniferous. Fish remains are abundant.

The Magnesian Limestone division varies a good deal from place to place; in Durham it is nearly all dolomitic limestones, while in Nottinghamshire there is a good deal of marl and sandstone. It is in the last named area that the difficulty of determining the exact relations of Magnesian Limestone and Bunter arose. At Market Weighton in East Yorkshire a deep bore (to—3,100 feet O.D.) penetrated 800 feet of this series without reaching the base.

In Durham the series is subdivided as follows:

Magnesian Limestone Series . .	Upper Limestone. Middle Limestone. Unconformity. Lower Limestone.

A notable feature is the unconformity between the Lower and Middle divisions. The Lower is not usually further subdivided. The Middle division consists of the Bryozoa Reef below and the Brecciated Limestone above. The former seems to have functioned something like a modern coral reef, while the cause of the brecciation, which was contemporaneous, is not clear. The Upper division consists of the Flexible Limestone at the base, the Concretionary or Cannon Ball Limestone in the middle and the Hartlepool Dolomites at the top. The Cannon Ball Limestone contains remarkable structures, to be seen in all geological collections, some spherical or simply nodular, others simulating fossils, such as corals, or architectural ornamentation. The cause of this phenomenon is still obscure, but it may be noted that the concretions consist of calcite, which has apparently crystallised out from the original dolomite. This rock is well seen on the coast of Durham, near Sunderland. The highest division like most of the rest of the series is highly dolomitic owing to the high salinity of the land-locked sea in which it was formed.

The northerly continuation of the upper division (Trias) on the east of the Pennines is very like that of the Midland area, but actually our knowledge of it is rather limited, especially in Yorkshire, where it underlies the Glacial deposits and alluvium of the Vale of York, and exposures are scarce. The smooth boundary shown on all the maps between the Permian and Trias in North Yorkshire is mainly hypothetical and further south most of the modern information has been obtained from bores and shaft sinkings during the development of the concealed coal-field which underlies the New Red rocks from Nottingham about as far north as Selby and perhaps as far east as Lincoln.

In Nottinghamshire the Bunter begins to change its character: the pebble beds, which make a considerable show in Sherwood Forest, disappear near Doncaster and it is not possible to divide Bunter from Keuper.

In Notts, the sandstones often form rather higher ground than the marls and such sandstones are often described geologically as 'skerries.'

Little is known of the succession in the Vale of York and in Cleveland, where it forms a flat drift-covered plain at the foot of the Hambleton and Cleveland Hills. Near Middlesbrough several bores show that the succession consists of red sandstones with marl partings above and mainly marl below, where gypsum bands appear and important beds of salt and anhydrite, which are the reason for the location of the great chemical works at Billingham, just north of the Tees.

North-western District

In the Eden Valley and north Cumberland the succession is very different though a broad correlation can be made. The succession in the whole area can be generalised as:

Trias	Stanwix Shales. Kirklinton Sandstone. St. Bees Sandstone.
Permian	Magnesian Limestone. Hilton Plant Beds. Penrith Sandstone.

These divisions are very unequal in thickness and some of the dividing lines in the upper part are rather vague. There is also great lateral variation in thickness in individual beds.

The Penrith Sandstone is really only developed in the Eden valley. For brevity it is so described in the table but in reality more than half of it, where thickest, consists of two great belts of a rock locally known as Brockram.

This rock is a breccia of angular fragments of Carboniferous Limestone in a red sandy matrix, obviously a scree deposit. It has been suggested that the material came from the scarp of the great Pennine fault which bounds the Eden valley on the east and was then supposed to be still moving. But there is some evidence that the material came from the west, from the border of the Lake District, so its source cannot be regarded as established. There are two Brockrams; one at the base, with a maximum thickness of 1,500 feet, and another towards the top, perhaps 1,000 feet higher in the series. The Penrith Sandstone proper is almost certainly a desert deposit. It is bright red in colour and contains both millet seed sands and recrystallised sand grains (see p. 163). It may be as much as 1,000 feet thick.

The Hilton Plant Beds, east of Appleby, consist of some 150 feet of sandy strata with obscure plants, apparently the same species as in the eastern Marl Slate.

Above this comes an attenuated representative of the Magnesian Limestone, which is really not much more than a sandstone with a dolomitic cement, about 25 feet thick at the most. This appears to indicate a feeble connection with the eastern basin over Stainmoor, and soon dies out northwards.

Next comes locally a bed of gypsum and anhydrite at the base of the St. Bees Shales, which pass up rather vaguely into the St. Bees Sandstone. This is fairly thick in the Eden valley, perhaps 1,500 feet at the north end: it is a red micaceous sandstone, thus differing from the Penrith Sandstone below, which like most wind-blown sands contains no mica. Here the highest bed seen is the Kirklinton sandstone, another red formation. West of Carlisle this is succeeded by the Stanwix

shales. No Rhaetic has been seen, though a small patch of Lias is known to exist.

In the West Cumberland coal district, the New Red begins with a Brockram followed by grey beds, a thin inconstant Magnesian Limestone and then more Brockram. At Seascale the St. Bees beds were found in a bore to be 2,000 feet thick and the Kirklinton above is equally thick. It seems clear from this neighbourhood that Brockrams may develop at any horizon and should be regarded as a facies and not a definite stratigraphical unit.

Near Ingleton and Clitheroe there are two small patches of New Red rocks, but a more important development of the lower part of the system is found near Manchester. This may be divided into the Collyhurst Sandstone below and the Manchester Marls above. The lower division varies in thickness in different places up to 800 feet, but is sometimes absent. It varies in thickness on opposite sides of some of the big faults of the coalfield, showing that these were moving in New Red times. The Manchester Marls are red or variegated and contain a few fossils, enough to fix their age. Still higher is a thin band of unfossiliferous Magnesian Limestone, so the succession shows a resemblance to the Eden valley.

The upper part of the system has a wide extension in south Lancashire, but is largely hidden by drift. It seems to be chiefly Keuper Marls, and there is an important bed of rock-salt near Fleetwood.

The fauna of the inland sea facies of the lower New Red System is of a special type owing to unfavourable conditions: most of the species are survivals from the Carboniferous, but the corals, echinoderms and cephalopods had almost disappeared. No trilobites are known in Britain, but one or two species have been found abroad. Several genera of brachiopods, lamellibranchs and gastropods still lived on, though with few species. The brachiopods *Productus horridus* and *Spirifer alatus*, and the lamellibranchs *Schizodus schlotheimi* and *S. obscurus* are among the best known and gastropods such as *Turbo helicinus* are often abundant. Polyzoa (Bryzoa) sometimes form the greater part of the limestone bands; *Fenestella retiformis*, is a characteristic species. Fish are rather abundant, especially in the Marl Slate, such as *Platysomus* and *Palaeoniscus*.

Scotland

In Ayrshire, Dumfriesshire, on the shores of Loch Ryan in Wigtownshire, and in the isle of Arran, a series of red sandstones, breccias and conglomerates lies unconformably upon the older rocks. No fossils have been found in them, and their age is still uncertain. They have been referred sometimes to the Permian, sometimes to the Trias. In their general character they resemble the breccias of the Midlands and of Devonshire, and were evidently formed under similar conditions.

In Ayrshire the series rests unconformably upon the Coal Measures. At the base are contemporaneous lavas and tuffs, and with these are associated numerous volcanic rocks which pierce the Coal Measures. Many of the volcanic rocks of Fifeshire probably belong to the same period.

Small patches of undoubted Trias occur in the Western Islands and upon the Western Coast; but by far the most interesting of the Scottish Triassic rocks are the Elgin sandstones, which are found on the Elgin coast near Lossiemouth. They lie unconformably upon the Old Red Sandstone, and have yielded a remarkable series of reptilian remains, including Dicynodonts (e.g. *Gordonia* and *Geikia*), Rhynchocephalia (*Telerpeton* and *Hyperodapedon*), and crocodiles (e.g. *Stagonolepis* and *Ornithosuchus*).

Ireland

In Ireland New Red rocks are found only in the north-east. The largest area is that of Belfast Lough, extending up the valley of the Lagan, and there are outcrops at intervals round the edges of the great basaltic plateau of Antrim. They consist of red and brown sandstones and marls, with gypsum and rock-salt, which has been extensively worked at Carrickfergus.

The Rhaetic Series

As before mentioned the Rhaetic Series differs markedly from all the other divisions of the New Red system. It marks the end in Britain of the continental period and the oncoming of the great marine transgression of the Lower Jurassic. By the end of Keuper times England had been worn down to a peneplain and the sea must have overflowed this suddenly and uniformly, so that the Rhaetic Series is curiously uniform over its whole outcrop, so far as it is seen, from Devonshire to Yorkshire. The fauna is definitely marine and is clearly of Jurassic type, the main difference being in the absence of ammonites, which had not yet arrived in this region, though they had long been abundant in central Europe, especially in Tirol (see p. 381), where the Rhaetic beds reach a very great thickness and form a large part of the Dolomites.

The Rhaetic Series is best seen on the coast close to the boundary between Devon and Dorset, near Lyme Regis, and in the Severn estuary, especially at Penarth, near Cardiff, whence it has been called the Penarth Series.

In Devon the coast section shows—

White Lias	25 feet
Black Shale	18 „
Grey Marls	30 „

The Grey Marls, which are passage beds, are either green, cream-coloured or black and show a transition from the Keuper: they are perhaps really only a bleached form of the top beds of the Keuper. The Black Shales contain *Avicula contorta*, *Cardium rhaeticum* and other marine forms. At the base is a bone bed with fish remains, etc., which doubtless marks the sudden incursion of the sea. At the base of the White Lias is a bed of 'Landscape Stone' or Cotham Marble such as is to be seen in all museums, about 9 inches thick, while the rest of it is a white limestone with marine fossils. The older writers, who gave the name 'White Lias' showed a true appreciation of its real affinity to the Jurassic.

At Penarth the sequence is thinner, simpler and more clear. The succession is, Avicula Shales 20 feet and White Lias 11 feet. The shales are separated from the Keuper by a sharp plane of erosion with a bone bed about an inch thick, as a rule, thicker in occasional pockets. This contains fish scales and teeth and coprolites. This marks the destruction of fish life consequent on the sudden incursion of the sea. There are other bone beds higher in the series. Lithologically the rocks above are like those on the Devon coast, but the whole changes a good deal, becoming more calcareous, when followed westwards. The Rhaetic is also well seen at Aust Cliff and other localities on the Gloucestershire side of the Severn.

Throughout the Midlands exposures are poor as a rule and it is not necessary to give details, but it is known from bores that the series extends with much the same characters as far as the mouth of the Tees, though it is not seen on the coast; the New Red-Lias junction is there below sea-level, being buried under a great thickness of drift.

Grey shales with Rhaetic fossils are known near Belfast, and Rhaetic fossils have been found in large blocks of rock engulfed in a volcanic neck in Arran.

CHAPTER XXII

THE JURASSIC SYSTEM

The Jurassic beds of England (Fig. 117) form an almost continuous belt stretching from the coast of Yorkshire south of the Tees to the Dorset coast about Lyme Regis and Weymouth. The breadth of the belt varies considerably. It is widest towards the middle, where it spreads from the neighbourhood of Leicester to King's Lynn in Norfolk; but in this region it is partly covered by the alluvial deposits of the Fens. It is narrowest in South Yorkshire, where, indeed, for a short distance it is completely overlapped by the Cretaceous beds.

Near the Bristol Channel there are many patches now cut off from the main band. At a greater distance are the outliers of Lias on the border of Cheshire and in Cumberland near Carlisle.

That, originally, the Jurassic deposits had a very much wider extension is shown by the occurrence of small patches in the north-east of Ireland, in the Hebrides, and upon the western and eastern coasts of northern Scotland.

Lithologically, the system consists chiefly of clays and limestones. Most of these are marine in origin, but some are deltaic, estuarine or fluviatile, and occasionally there are even remains of terrestrial soils. Some of the subdivisions pass almost unaltered throughout the length of England, but others show considerable variations.

The general character of the changes will be most readily understood if we take the southern development as a type. Here the system consists of an alternating series of clays and limestones (Fig. 118). The divisions which in the south consist of clay, remain clay throughout the whole of England; those which are calcareous in the south, change their character as they are traced towards the north. The changes are shown in the following table, in which, it must be understood, only the general character of the deposits is broadly indicated:

	South of England.	Middle of England.	North of England.
Purbeckian, Portlandian . . .	limestone	absent	absent
Kimmeridgian. . .	clay	clay	clay
Corallian	limestone	clay	limestone
Oxfordian	clay	clay	clay
Bathonian, Bajocian (Lower Oolites.)	limestone	limestone sands	sands
Lias	clay	clay	clay

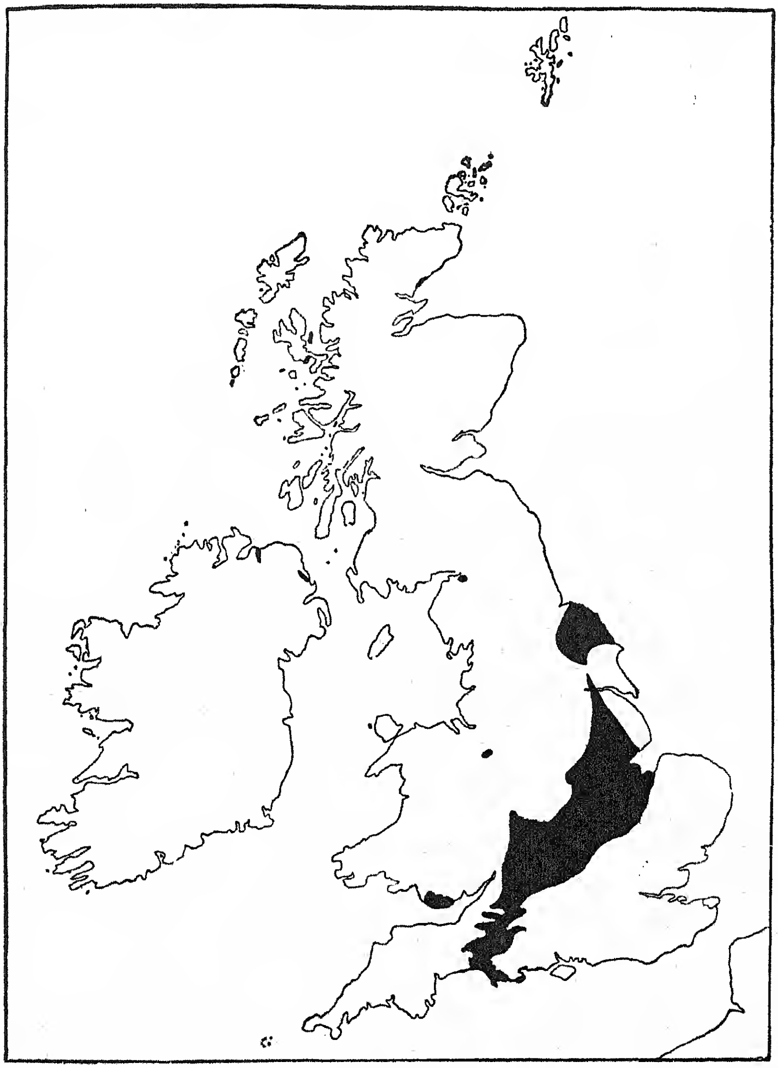


FIG. 117.—THE JURASSIC SYSTEM.

After various changes during the last hundred years, which need not be discussed here, the Jurassic System is now generally subdivided as below:

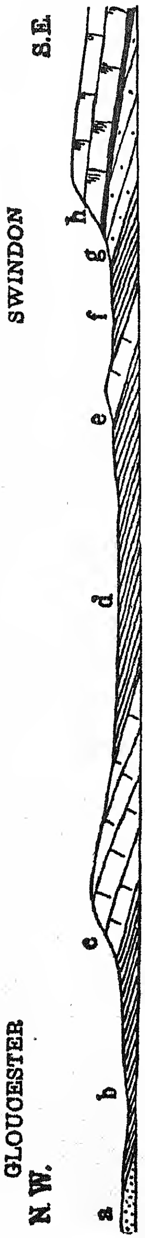


FIG. 118.—DIAGRAMMATIC SECTION FROM GLOUCESTER TO SWINDON.
a, Trias; *b*, Lias; *c*, Lower Oolites; *d*, Oxford Clay; *e*, Corallian; *f*, Kimmeridge Clay; *g*, Portland and Purbeck beds; *h*, Cretaceous.

Upper Jurassic	Purbeckian. Portlandian. Kimmeridgian. Corallian. Oxfordian.
Middle Jurassic	Bathonian. Bajocian.
Lower Jurassic	Lias.

If the maximum known thicknesses of the different subdivisions are added together the total comes to several thousand feet, but owing to great local variations such a proceeding is of no value, since the thick or thin developments of the various divisions do not all come in the same place, and it is impossible to say that the whole system is thickest or thinnest anywhere. Moreover, in several subdivisions local unconformities and non-sequences are common, owing to minor but significant earth-movements, which were largely responsible for the complicated stratigraphy of this system.

The influence of the plateau of ancient rocks under south-eastern England on Mesozoic sedimentation will be discussed in the chapter on the Cretaceous system, to avoid unnecessary repetition.

Fauna and Flora.—Since the system consists chiefly of marine deposits, the greater number of the fossils are marine, but deltaic and terrestrial forms occur. The period has been called 'the Age of Cycads,' 'the Age of Ammonites,' and 'the Age of Reptiles,' according to the point of view of the writer; and these three names indicate the most striking features of the fauna and flora.

Plants are found at several horizons, and especially in the deltaic and terrestrial deposits. The vegetation is becoming more nearly related to modern types. Cycads were the dominant group, e.g. *Williamsonia*, *Cycadeoidea*, *Otozamites*. Equisetaleans and Ferns were well represented: Ginkgoaleans were conspicuous, such as *Baiera* and *Ginkgoites*, and so were the Conifers, including

Araucarites and *Sequoiites*. The Pteridosperms include such genera as *Thinnfeldia*. Of especial interest are the Caytoniales, believed to be primitive Angiosperms.

Corals are abundant in the limestones, but rare in the clays. The rugose corals of the Palaeozoic period have disappeared, and in their place are aporose and perforate types. Amongst the common genera are *Montlivaltia, Isastrea, Thecosmilia* and *Thamnastraea*.

Of the Echinoderma the crinoids are relatively much less abundant than in the Palaeozoic rocks, while the echinoids have become far more important. The crinoids include *Pentacrinus* and *Apiocrinus*. The echinoids, which occur chiefly in the limestones, include *Cidaris, Hemicidaris, Acrosalenia, Nucleolites* (= *Echinobrissus*), *Holectypus* and *Pygaster*.

Brachiopods are still common, but nevertheless they no longer preponderate as in the Palaeozoic era. The period is characterised by the large number of species and individuals belonging to the genera *Terebratula, Magellania* and *Rhynchonella*.

Of the Mollusca, lamellibranchs, gastropods and cephalopods are all abundant. The most striking feature of the period is the great development of the ammonites, which occur both in the clays and in the limestones. So abundant and so widespread are they, and so varied in form, that they serve to divide the system into zones which can be recognised over a large part of the globe. Belemnites also appear, and attain their maximum in this period. They are found chiefly in the clays.

So far as vertebrates are concerned, the period was certainly the age of reptiles. They played the dominant part in the sea (Ichthyopterygia, Sauropterygia), on the land (Dinosauria) and in the air (Pterosauria). The earliest known birds occur in the Jurassic system, two skeletons having been found at Solenhofen, in Germany. They are known as *Archaeopteryx*. The tail was composed of a number of separate vertebrae, with a pair of feathers to each. Mammalia are found in England in the Stonesfield Slate (Bathonian) and in the Purbeck beds. Most of the forms appear to have been marsupials, but some probably belong to a more primitive group (Prototheria).

LOWER JURASSIC

The Lias

The Lias is essentially an argillaceous formation. It consists chiefly of grey or blue-grey clays or shales, which give rise to some of the richest pasture-lands of England. Occasionally the clays are sandy; more often they are calcareous or marly. Beds of limestone are some-

times abundant, especially in the lower part of the series; but the Liassic limestones are quite unlike the limestones of the Carboniferous and Silurian systems. They are not coral-reefs, nor are they often shell-banks. Most of the bands, indeed, are only indirectly of organic origin. They consist largely of detrital material, which seems to have been derived from the denudation of pre-existing limestones. They were, in fact, calcareous muds laid down near the shores of an old land in which the Palaeozoic limestones were prominently exposed. In consequence of this mode of formation, the Liassic limestones are seldom pure. They are almost always argillaceous or ferruginous. They seem, moreover, to have been deposited in shallower water than the clays. The summits of the Mendip Hills rose as islands above the Liassic sea, and near the Mendip ridge the limestones thicken at the expense of the clays. The fossils also indicate the neighbourhood of land. Several bands contain remains of winged insects in such abundance that they are locally known as 'insect limestones.'

In some districts the Lias includes valuable beds of iron-ore; a mixture of the clays and limestones makes good cement; and in places there are seams of lignite or masses of jet. Pyrite is often abundant, and the shales may then serve as a source of alum.

Although the sands and limestones appear to indicate the neighbourhood of land, the whole of the Lias was laid down beneath the sea. The insects found in certain beds are associated with ammonites and other shells, and everywhere the fauna of the Lias is distinctly marine. But, even in the limestones, it was the fauna of a muddy sea.

Corals, echinoids and polyzoa are rare. A few genera of crinoids, however, such as *Pentacrinus* and *Extracrinus*, are locally abundant. Brachiopods are common, *Spiriferina walcotti* and *Rhynchonella tetrahedra* being two of the characteristic species. Gastropods are not abundant, and by far the most prominent of the Mollusca are the lamellibranchs and ammonites. The lamellibranchs include *Gryphaea arcuata* (perhaps the most common of all the Lias fossils), *Hippopodium ponderosum*, *Lima gigantea* and *Nuculana ovum*. The ammonites are used as zone-fossils, and the names of the principal species will be found in the list of zones given below. The insects have already been referred to. They include representatives of several of the living orders, such as Orthoptera, Diptera, Neuroptera, Coleoptera and Hemiptera. Many genera of fish occur; but the most remarkable of the vertebrates are the reptiles. Amongst these are the large saurians, such as *Ichthyosaurus* and *Plesiosaurus*, which lived in the sea; and the flying Pterodactyls, such as *Dimorphodon*. Plants are not very common; but they occur in several localities. Cycads are the predominant group.

The Lias is divided into a number of ammonite zones as follows:

Upper Lias.	*Lytoceras jurense.* *Hildoceras bifrons.* *Harpoceras falcifer.* *Dactylioceras tenuicostatum.*
Middle Lias.	*Paltopleuroceras spinatum.* *Amaltheus margaritatus.*
Lower Lias.	*Prodactylioceras davoei.* *Tragophylloceras ibex.* *Uptonia jamesoni.* *Echioceras raricostatum.* *Oxynoticeras oxynotum.* *Asteroceras obtusum.* *Arnioceras semicostatum.* *Coroniceras bucklandi.* *Scamnoceras angulatum.* *Psiloceras planorbe.*

These zones are subdivided into innumerable sub-zones by specialists, but nearly all authorities give a different list, so no good purpose would be served by enumerating them here.

Lithologically the general character of the Lias remains more or less constant from Dorsetshire to Yorkshire, but there are considerable local variations in thickness, especially in the south-west, as will be noted later.

South of England.—In the south of England the succession is as follows:

Upper Lias. Clays or shales, becoming sandy towards the top, and with a pale-coloured argillaceous limestone at the base.

Middle Lias. Micaceous sandy clays with a ferruginous limestone, the 'Marlstone,' at the top.

Lower Lias. Grey marls and clays, with bands of limestone.

Generally the limestones predominate at the base of the series, and the Lower Lias may often be divided into a calcareous division below and an argillaceous division above; but the development of the limestones is irregular, and no definite boundary can be drawn between the two divisions.

The Middle Lias is less calcareous and more sandy; but the Marlstone at the top, though thin, is very persistent. The clays and sands belong generally to the *margaritatus* zone, the Marlstone to the *spinatum* zone.

The limestone at the base of the Upper Lias contains remains of reptiles, fish, crustaceans and insects, together with marine fossils. This is followed by clays and shales, which become sandy towards the top; and frequently there is a considerable thickness of sands between the Upper Lias Clays and the limestones of the Inferior Oolite. But the horizon at which the sands begin is variable, and their upward limit is inconstant. In some places the highest zones of the Lias consist of clay. In other cases the sands have been removed by denudation before the deposition of the succeeding series. In the neighbourhood of the Mendip Hills and in other places the Upper Lias is reduced to a very few feet.

Midlands.—In the Midlands the same general succession can be recognised. The Lower Lias consists chiefly of limestones below and clays above, yielding much material suitable for cement making. The Middle Lias consists of sands and clays, capped by the Marlstone, in many places a shelly limestone, and in Oxfordshire (Banbury) and in Leicestershire a valuable iron-ore. The Upper Lias commonly begins with an insect limestone, and this is followed by clays and shales; but the shales no longer pass upwards into sands. The junction with the Inferior Oolite is sharply defined, and in places presents evidence of erosion.

Lincolnshire and Yorkshire.—Towards the north certain lithological changes occur. As far as Market Weighton there is a considerable development of argillaceous limestones at the base; but in the north of Yorkshire the whole of the Lower Lias consists principally of shales with thin bands of shelly limestone.

But the most remarkable feature in the northern area is the presence of beds of iron-ore, sideritic or chamositic oolites, which have given rise to industrial developments of the highest importance in North Lincolnshire and Cleveland. For an account of the origin and character of the Jurassic iron-ores in general see Chapter IX.

The iron-ore of Frodingham, in Lincolnshire, lies in the Lower Lias, and consists of rather thin-bedded alternations of limonite-oolite and ferruginous limestone.

It is, however, in the Middle Lias of North Yorkshire that the development of iron-ore is greatest. There the Middle Lias may be divided into a Sandy Series below and an Ironstone Series above. The Sandy Series includes the lower part of the *margaritatus* zone, and extends downwards into the Lower Lias. It consists of alternations of hard sandy shales and thin, micaceous, calcareous and ferruginous sandstones. The Ironstone Series includes the upper part of the *margaritatus* zone and the whole of the *spinatum* zone, and consists of numerous alternations of shale and ironstone. It is from these beds that the greater part of the Cleveland iron-ore is obtained. The principal band of ironstone is the Cleveland Main Seam, which contains *Paltopleuroceras spinatum* and appears to be the equivalent of the Marlstone. Other seams have also been worked. In general the ironstone bands are thickest and most important towards the north-west, while towards the south and east they split and gradually die out.

The Upper Lias of Yorkshire consists almost entirely of micaceous shales, with occasional thin hard bands which may be calcareous, ferruginous, or sandy. Near Whitby it may be divided lithologically into—

Alum Shales.
Jet Rock Series.
Grey Shales.

The *jurense* zone has not been found except for a mile on the coast between Blea Wyke and Peak and more extensively in some of the western interior dales.

The jet of the *falcifer* zone occurs as isolated lumps, and is very irregular in distribution. Its origin and nature are described in Chapter IX.

The Alum Shales are grey crumbly shales with much disseminated pyrite, which causes a yellow incrustation on the weathered fragments. These shales were formerly extensively used for the manufacture of alum, but the industry is now extinct in this district.

Scotland.—That the Lias sea extended into Scotland is shown by the occurrence of Liassic deposits, in part marine, in the Hebrides, and upon both the west and east coasts of the mainland—upon the eastern coast as far north as Dunrobin Castle in Sutherland. But there are clear indications that these deposits were laid down near the margin of the ancient sea. Upon both coasts the lowest beds are littoral in origin, consisting largely of sands and conglomerates. The upper part of the Lower Lias, on the other hand, and both the Middle and the Upper Lias, do not differ greatly from the corresponding beds in England.

In the west of Scotland the Mesozoic rocks owe their preservation in part to faulting, but chiefly to the protection afforded by the great lava-flows of the Tertiary era. They are exposed, therefore, only where the overlying basalts have been removed by denudation, and continuous sections are rare. The finest is that upon the east coast of the island of Raasay, where there is a thick bed of oolitic iron-ore.

On the East Coast the Lower Lias is found at Dunrobin Castle, in Sutherland. The lowest beds are sandstones, shales and beds of coal, and are evidently of deltaic origin. These are followed by sandstones, limestones and clays with a marine fauna.

The Middle Lias has not been found in situ, but boulders with Middle Lias fossils are so abundant in the glacial clays of Elgin that their source can hardly have been far away.

Ireland.—In Ireland, as in the Western Isles, the Lias owes its preservation to the outflows of Tertiary lava which overspread the north-eastern part of the country. It is accordingly only around the margin of the Antrim plateau that any deposits of this period are found. They consist of shales, clays, and limestones, with typical Lower Lias fossils. No trace of the Middle or Upper Lias has been found, and even the higher zones of the Lower Lias are not seen.

MIDDLE JURASSIC

THE LOWER OOLITES

In the south of England the Lias is succeeded by a series of limestones, with some clays and sands, which are conveniently known by the old-fashioned name of Lower Oolites. They are commonly divided into two series, Bajocian (from Bayeux in Normandy) below and Bathonian (from Bath) above. Some authors subdivide these groups again, confining the names just given to parts only of the respective divisions, but over a large part of England all these dividing lines are difficult to recognise.

The boundary between the Lias and the Lower Oolites varies much in character: in some places there appears to be conformity, but in others there is evidence of uplift and considerable erosion between the two periods of deposition.

Although consisting largely in the south of calcareous rocks, the Lower Oolites are shallow-water deposits. The limestones are usually oolitic or pisolitic, and as a rule they are conspicuously current-bedded. The sands, too, are generally false-bedded, and it is only the occasional beds of clay that appear to have been laid down in tranquil waters. Everywhere in the south of England the deposits are marine, but they were formed in a shallow sea disturbed by changing currents. Owing to the fluctuations of these currents the individual beds are somewhat inconstant, and frequently there are gaps in the succession. In some cases the gaps may be due simply to absence of deposition, but sometimes a temporary increase in the strength of the currents has resulted in the removal of a part of the material already laid down.

Traced northwards along the Jurassic outcrop the beds lose their calcareous character and the limestones are replaced by sands. The sands at the base are usually marine, but in Northamptonshire and Rutland fresh-water deposits appear above them, and the change of facies becomes more and more pronounced towards the north. The changes are very complex, and are shown diagrammatically in Fig. 119. In accordance with the lithological variation there is a corresponding change in the fossils, and thus it is impossible to distinguish in the north of England all the minor subdivisions recognised in the south.

In the south, where calcareous beds predominate, ammonites, gastropods, lamellibranchs, brachiopods and echinoids are abundant. Corals and polyzoa are plentiful in some beds, and many sponges have been obtained. On the other hand, plants, crustaceans, insects and vertebrates are rare except in the Stonesfield Slate. In this deposit, however, a remarkable fauna has been discovered, including mammals (*Amphilestes*. *Phascolotherium*, etc.), ornithosaurs and other reptiles, fish,

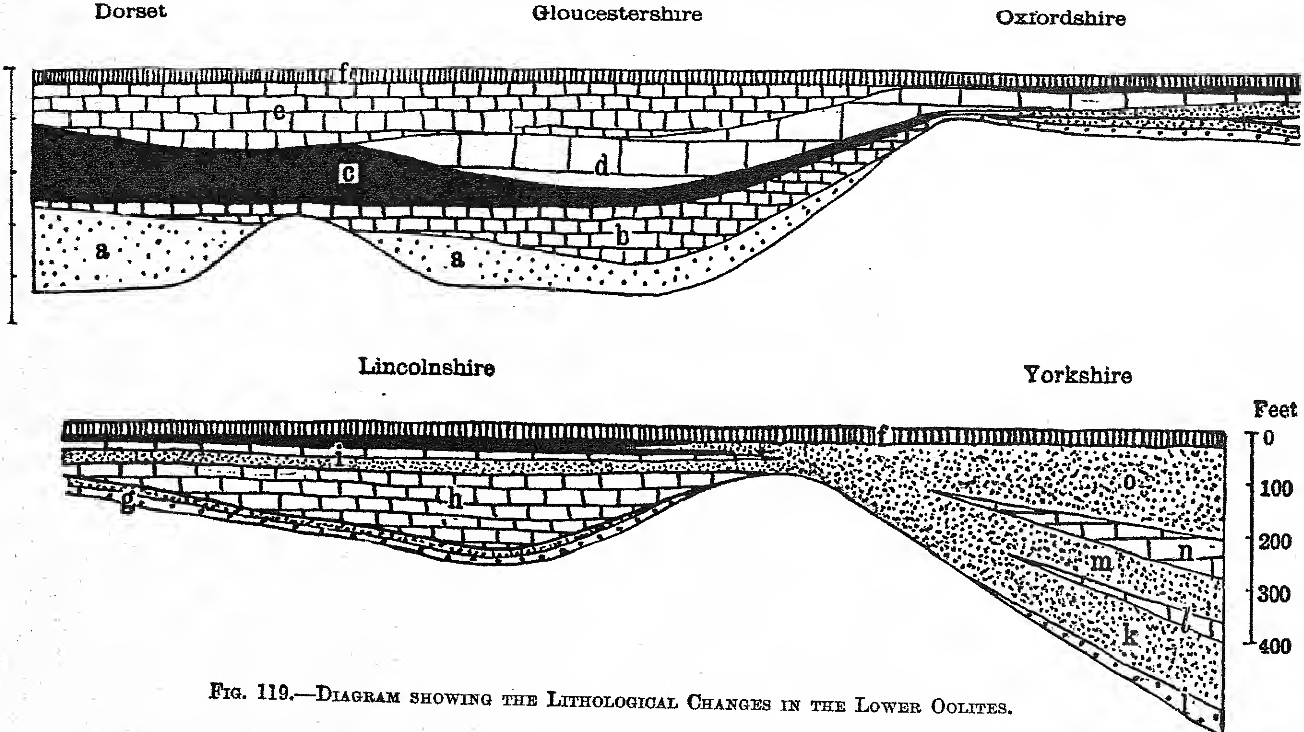


Fig. 119.—Diagram showing the Lithological Changes in the Lower Oolites.

South of England: *a*, Midford Sands (belonging in part to the Lias); *b*, Inferior Oolite; *c*, Fuller's Earth; *d*, Great Oolite; *e*, Forest Marble; *f*, Cornbrash.
Lincolnshire: *g*, Northampton Sands and Lower Estuarine Series; *h*, Lincolnshire Limestone; *i*, Upper Estuarine Series, Great Oolite Limestone, Great Oolite Clay; *f*, Cornbrash.
Yorkshire: *j*, Dogger; *k*, Lower Estuarine Series; *l*, Millepore Limestone; *m*, Middle Estuarine Series; *n*, Scarborough Limestone; *o*, Upper Estuarine Series; *f*, Cornbrash.

crustaceans, insects, marine mollusca, etc., together with remains of plants.

In the north of England there are occasional bands with marine fossils; but the deltaic beds themselves contain chiefly plants and fresh-water shells. The common genera are the ferns, or fern-like forms, *Cladophlebis*, *Todites*, *Coniopteris*, *Laccopteris*, etc., and the cycads, *Williamsonia* and *Otozamites*.

In the south of England the Lower Oolites may be divided into a number of zones by means of the ammonites, but it is impossible to carry these zones into the north.

The South-western District.—The south-western district includes Dorsetshire, Somersetshire, Gloucestershire and a part of Oxfordshire. In spite of local variations, the following subdivisions may generally be recognised:

Great Oolite Series . . .	Cornbrash. Forest Marble and Bradford Clay. Great Oolite, with the Stonesfield Slate. Fuller's Earth.
Inferior Oolite Series . .	Inferior Oolite. Midford sands (in part).

Lithologically the Inferior Oolite series may be subdivided into the Midford Sands below and the Inferior Oolite Limestone above. But the sands between the Limestone and the clays of the Upper Lias are not everywhere at the same horizon, and there is thus considerable difficult in drawing the line between the Lias and the Lower Oolites. Usually the line is taken at the top of the Liassic *jurense* zone, and in that case most of the sands belong to the Lias, but in Dorsetshire they extend upwards into the Inferior Oolite, whilst in the Cotswolds this series is calcareous to its base.

An interesting feature of the Inferior Oolite is the occurrence in Gloucestershire of a local unconformity towards the top of the series: the highest division transgresses right across all the lower zones on to the Lias and Rhaetic and finally in Somerset on to the Carboniferous Limestone of the Mendips.

The Great Oolite series also consists chiefly of oolitic limestones, but there are considerable local variations in its development.

The lowest member of the series is the Fuller's Earth. It is a marly clay, blue, grey or yellowish in colour, but only the upper part yields the fuller's earth of commerce. The middle is often an earthy limestone, which is locally called the Fuller's Earth Rock. Amongst the characteristic fossils are *Teloceras subcontractum* and *Ostrea acuminata*. In Dorsetshire the Fuller's Earth is about 150 feet thick, but north and north-east of Bath it diminishes in thickness, and in Oxfordshire it becomes scarcely separable from the Stonesfield Slate.

The Great Oolite Limestone, or Great Oolite proper, consists of shelly

limestones or 'rags,' and fine oolites or freestones, with occasional layers of sandy marl. It attains a considerable thickness in Gloucestershire, where it yields the well-known Bath stone; but in Dorsetshire it becomes extremely thin or altogether dies out. As the Fuller's Earth thickens in this direction, it has been suggested that the two formations may be in part contemporaneous; but it is probable that the absence of the Great Oolite in the south is due in part to erosion.

The lower part of the Great Oolite is in general more sandy and flaggy than the upper, and it is to this part, where the flaggy structure is well developed, that the name of Stonesfield Slate has been applied. The most remarkable feature of the Stonesfield Slate is that it has yielded remains of mammalia, reptiles, fish, insects and plants, as well as the usual marine fossils of the Great Oolite.

Amongst the common fossils of the Great Oolite are *Terebratula maxillata* and *Acrosalenia hemicidaroides.*

The Forest Marble, together with the Bradford Clay, is a very variable series. It consists of shelly oolitic limestones, thin flaggy limestones, clays and shales, with, in some places, beds of sand. Near Bradford-on-Avon and other places the lower beds are clay with an abundance of fossils, and form the so-called Bradford Clay; but the Bradford Clay is no more than a local facies of the Forest Marble.

In Gloucestershire the Forest Marble rests upon the Great Oolite, but south of the Mendips it overlaps that formation and lies directly on the Fuller's Earth. The common fossils of this subdivision are *Magellania digona, Rhynchonella varians, Terebratula coarctata* and *T. maxillata. Apiocrinus parkinsoni* is abundant in the Bradford Clay, but it grew upon the Great Oolite, and apparently was killed by the incursion of the muds which now form the Bradford Clay.

The Cornbrash is the most uniform of all the subdivisions, and the only one which stretches almost unaltered along the length of England. Everywhere it consists of tough irregular layers of earthy and shelly limestone, and where it is exposed in quarries it usually presents a very rubbly appearance. There is an absence of the marked false-bedding so conspicuous in the beds below, and it was evidently deposited in more tranquil waters. Its thickness is generally from 10 to 25 feet. *Clydoniceras discus, Terebratula intermedia* and *Magellania lagenalis* are amongst the characteristic fossils.

Central District.—The Central District may be taken to extend from Oxfordshire to the north of Lincolnshire.

From Dorsetshire to the north of Gloucestershire the outcrop of the Lower Oolites runs from south to north; but here the direction changes, and through Oxfordshire the trend is more nearly from west to east. With the alteration in direction there begins a change in the nature of the deposits. Towards Fawler, in Oxfordshire, the whole series rapidly decreases in thickness, and the lower members of the Inferior Oolite

are completely overlapped. Beyond Fawler the lower beds reappear; but their character is altered. At the base are brown ferruginous sands and calcareous sandstones. At first very thin, these sandy beds thicken towards the north-east, and are known as the Northampton Sand.

As the Northampton Sand develops at the base of the Inferior Oolite, the rest of that series is replaced by lighter coloured sands with plant-remains. These are known as the Lower Estuarine series.

A similar change takes place in the lower part of the Great Oolite series, and the general result of all these changes is that from Northamptonshire to Lincolnshire the Lower Oolites may be divided as follows:

Cornbrash.
Great Oolite Clay.
Great Oolite Limestone.
Upper Estuarine Series.
Lincolnshire Limestone with the Collyweston Slate.
Lower Estuarine Series.
Northampton Sand.

There are, however, local gaps in the succession, and it is very doubtful whether any of these beds are really of estuarine origin. They are probably deltaic, as in Yorkshire.

The Northampton Sand includes beds of hard calcareous sandstone, ironstone and occasional sandy oolitic limestones. The thickness is variable, but probably never exceeds forty feet. Fossils are not often abundant. They are mostly marine forms, and amongst them are *Lytoceras jurense*, *Lioceras opalinum*, and *Ludwigia murchisonae*. Apparently, therefore, the series is in part of Liassic age, but in general it rests upon an eroded surface of the Lias Clay. Economically the Northampton Sand is important on account of valuable beds of iron-ore, now the basis of a most important industry.

The Lower Estuarine Series consists of white, brown and grey sands, with inconstant beds of clay. Remains of plants occur, but other fossils are rare.

In North Oxfordshire and a large part of Northamptonshire these beds are followed directly by the Upper Estuarine Series. The junction is there eroded, and there is often a distinct unconformity between the two series. North of the Welland, however, a thick mass of limestones intervenes and the unconformity disappears. This is the Lincolnshire Limestone, which has yielded the famous Barnack and Ketton building stones. The Collyweston Slate is merely the name applied to beds of flaggy sandy limestone at its base.

The Upper Estuarine Series consists of blue, purple, white and variegated clays, more or less sandy, with occasional irregular layers of limestone. They contain chiefly plant remains and fresh-water shells such as *Cyrena* and *Unio*; but marine fossils are also found.

The Great Oolite Limestone and Great Oolite Clay are both marine deposits, and probably represent the Forest Marble and a part of the Great Oolite of the south-western district.

The Cornbrash presents the same general characters as in the south.

Yorkshire.—In the north of the county the equivalent of most of the Lower Oolites has long been known by the unfortunate name of the 'Estuarine Series.' It shows no characteristics of true estuarine strata and in fact consists of typical delta deposits, a miniature coal-field, sandstones and shales with thin coals, seat-earths, marine bands and washouts. It is believed that the transition from the Lias is nowhere complete, at least some part of the *jurense* zone being always absent, while in many places the gap is much greater, indicating a considerable amount of uplift and erosion. However, the Dogger in the broadest sense is always marine, as is also the Cornbrash at the top.

The fresh-water deposits are divided into three series by two intercalated marine bands, and there is a third, the Ellerbeck Bed, discovered after the nomenclature had become standardised, in the middle of the lower series. The succession is as follows:

Cornbrash.
Upper Estuarine Series.
Scarborough Limestone.
Middle Estuarine Series.
Millepore Limestone.
Lower Estuarine Series.
Dogger.

The Dogger is a very variable formation. It includes beds of sandstone, limestone and shale, and valuable bands of iron-ore, and it is often nodular or concretionary in structure. As the uppermost zone of the Lias is usually absent beneath the Dogger, there must be a certain amount of unconformity between the two series. But at Blea Wyke Point, near Ravenscar, below the Dogger proper, there is a series of sands with Lower Oolite fossils, passing downwards with one slight break into the *jurense* zone of the Upper Lias. Within a mile to the west the Blea Wyke beds have entirely disappeared, and the Dogger rests upon an eroded surface of the Lias. The disappearance of the Blea Wyke beds coincides with a considerable fault known as the Peak fault; and it is believed that this fault has some relation to the deposition of the beds. On the north-west side the sea-floor was raised within the reach of waves and currents, and erosion took place; on the south-east side deposition was nearly continuous from the Lias to the Oolites.

The 'Estuarine' beds consist of irregular alternations of sandstone and shale, with thin seams of coal and occasionally a little ironstone. The Lower series is the most arenacous of the three, and the Upper

the most shaly. Plant remains are found in all, but they are particularly abundant and well preserved in the Middle series, while the Upper series is almost barren except towards its base. *Cladophlebis, Coniopteris* and *Otozamites* are the commonest genera in the Lower Estuarine series; *Cladophlebis, Laccopteris,* and *Nilssonia* in the Middle Estuarine series.

The Millepore Limestone on the coast is not a true limestone. It is a hard calcareous sandstone with ferruginous partings. Inland, however, it is composed in part of oolitic limestone. It derives its name from the small polyzoan *Entalophora* (*Millepora*) *straminea,* which in some places crowds the surface of the beds.

The Scarborough Limestone also includes little real limestone, and consists chiefly of calcareous shales and sandstones and occasional coarse grits. It contains ammonites of Upper Bajocian age and it therefore appears that only the Upper Estuarine series and the Cornbrash can be assigned to the Bathonian.

The Cornbrash is a thin band of hard ferruginous limestone passing down into calcareous shale. It contains the characteristic Cornbrash fossils *Magellania lagenalis, M. obovata,* etc., but it is found only in North Yorkshire. South of a line drawn west from Filey, the Upper Estuarine series is followed directly by the Oxfordian.

Scotland.—Upon the western coast and in the Inner Hebrides the Lower Oolites are found in many places, from the Shiant Islands on the north to Ardnamurchan on the south. The best exposures are those in the islands of Raasay and Skye.

The Inferior Oolite series consists chiefly of sandstones and shales, with a limestone made of comminuted shells at the top. Ferns and cycads occur, and some of the beds are probably estuarine; but the greater part of the series contains marine fossils.

The Great Oolite series, on the other hand, seems to be almost entirely a fresh-water deposit. It consists at the top and bottom of dark shales with thin bands of limestone, and in the middle a great mass of sandstones and grits. The shales and limestones contain fresh-water shells (e.g. *Viviparus, Cyrena*) and ostracods (*Cypris*), but in the upper series there are beds completely made up of *Ostrea hebridica.* The sandstones have yielded little excepting remains of plants. Towards the base of the series numerous fish and reptilian remains have been found.

On the eastern coast the Lower Oolites occur near Brora, in Sutherland, and there are one or two smaller patches in Elgin. They consist chiefly of sandstones and shales, with layers of limestone and some thin seams of coal. The fossils are mostly fresh-water shells, plants, and the teeth and scales of fish. But *Ostrea* is also common. Probably, like the similar deposits on the western coast, they correspond with the Great Oolite series.

The Oxfordian Series

The variable group just described is followed conformably by a much more uniform series known as the Oxfordian. It consists for the most part of bluish, greenish, or lead-coloured clay, which usually becomes brown or yellowish at the surface. Generally the lower part is more or less laminated and shaly. Calcareous bands and irregular lines of septaria occur, and, as in most of the great clay formations, there is often much pyrite and selenite.

Towards the base of the clay there are inconstant beds of sand and calcareous sandstone, often with a more or less marked concretionary structure. In some areas these sandy beds become so prominent that they have received a special name, the Kellaways Rock, from a locality in Wiltshire. It is not developed in the Midlands, but in Yorkshire it is best seen. Hence the Oxfordian is divided lithologically into two groups.

2. Oxford Clay.
1. Kellaways Rock.

But the development of the sandy deposits varies considerably, and accordingly the line between the Kellaways Rock and the Oxford Clay does not run along a constant horizon.

The general uniformity of the Oxford Clay, the fineness of the material and the absence of false-bedding, indicate a deeper sea than that in which the Lower Oolites were deposited—a sea so deep or tranquil that the sediments lay beneath the limits of action of waves and currents.

The fossils of the Oxfordian are naturally such as lived in a muddy sea. Corals and echinoderms are rare. Neither brachiopods nor gastropods are particularly common, although some species are occasionally found in abundance. It is the lamellibranchs, especially the oyster-like forms, and the cephalopods, both ammonites and belemnites, that constitute the most characteristic part of the Oxfordian fauna. *Gryphaea dilatata* is one of the commonest fossils in the upper beds, while *G. bilobata* is found in the Kellaways Rock. Of the belemnites, *B. oweni* is the most widely known species. The ammonites, as in the other clay formations of the Jurassic system, serve as zone-fossils. Macrurous crustacea are fairly common, but brachyurous forms are rare. Fish are not very abundant. Remains of reptiles, such as *Megalosaurus*, *Ichthyosaurus*, *Pliosaurus*, etc., are found. Fragments of plants are sometimes numerous, but the species are unrecognisable.

Palaeontologically the Oxfordian may be divided into a number of ammonite zones, but they have not yet been traced across the country. In the south and centre of England the following broader divisions may be recognised :

Upper Oxford Clay.	*Creniceras renggeri, Cardioceras praecordatum.*
Middle Oxford Clay.	*Quenstedtoceras lamberti, Peltoceras athleta.*
Lower Oxford Clay.	*Cosmoceras jason, Cosmoceras duncani.*
Kellaways Rock.	*Sigaloceras calloviense.*

Owing to the general uniformity of the series, it is unnecessary to give any separate account of its development in different parts of England. Over most of the country it varies only in thickness and in the amount of arenaceous material at the base.

In Yorkshire, however, the facies of the Kellaways Rock extends upwards to the horizon of the Middle Oxford Clay, and even the Upper Oxford Clay loses its typical character and becomes a grey sandy shale in which fossils are generally rare. The total thickness is considerably less than in the south, but the massive sandstones of the Kellaways facies give rise to some remarkable scenery in the hills for many miles west of Scarborough.

The clay development in the Midlands is of very great industrial importance as a source of brick-clay, especially near Peterborough, and in Bedfordshire and Buckinghamshire.

Scotland.—In the islands of Skye and Eigg the Estuarine series, which is referred to the Great Oolite period, is followed by a mass of blue clays with subordinate bands of argillaceous limestone. They contain *Quenstedtoceras lamberti* and other fossils characteristic of the Oxford Clay.

In Sutherland the Oxfordian series consists of black shales and sandy clays, with a calcareous sandstone at the base. The latter is evidently the Kellaways Rock, and contains the Kellaways fauna. The shales and clays above contain typical Oxfordian fossils.

The Corallian Series

The Corallian, like the Lower Oolites, is a variable series, and exhibits two distinct facies. In the south of England and in Yorkshire it consists chiefly of calcareous rocks, while from Bedfordshire to Lincolnshire it is almost entirely clay.

The calcareous facies consists in general of shelly limestones, current-bedded oolites, masses of coral, together with occasional layers of sand or clay. Ripple-marks and worm-burrows are found in some of the sands, and lignite is not uncommon. Such deposits must have been formed in a shallow sea where the water was clear and free from mud.

The argillaceous facies, on the other hand, consists of finer sediment and shows no false-bedding. It was probably laid down in deeper but more muddy water.

In the calcareous beds corals, echinoderms, gastropods and lamellibranchs are the most abundant forms. Ammonites and belemnites are also found. Brachiopods and polyzoa are comparatively rare. Of the corals, *Isastrea explanata*, *Thecosmilia annularis* and *Thamnastrea arachnoidea* are the species most often found. *Nucleolites scutatus* is the commonest of the echinoids; *Hemicidaris intermedia*, *Cidaris florigemma* and *Pygaster umbrella* are also frequently met with. The gastropods include *Nerinaea*, *Pseudomelania*, etc. *Trigonia clavellata*

is one of the characteristic lamellibranchs. Amongst the principal ammonites are *Cardioceras cordatum* and *Perisphinctes martelli.*

The argillaceous facies contains few corals or echinoderms. Lamellibranchs, ammonites and belemnites are the characteristic fossils. The fauna is, to a large extent, a mixture of Oxfordian and Kimmeridgian forms, including, for example, the common Oxford Clay species *Gryphaea dilatata*, and the Kimmeridge Clay species *Ostrea deltoidea.* But it includes also a certain number of the characteristic species of the calcareous Corallian. The commonest fossil is *Ostrea discoidea.*

Owing to the great variability of the deposits, the lithological subdivisions are only of local value. After many changes the three following ammonite-zones are now generally recognised, but they cannot be traced everywhere and do not correspond exactly to lithological divisions:

3. *Ringsteadia anglica.*
2. *Perisphinctes martelli.*
1. *Cardiocerus cordatum.*

At one time *C. cordatum* was believed to be an Oxford Clay fossil: hence some confusion has arisen.

South-western District.—In the south-west of England the Corallian consists of calcareous grits, rubbly, shelly and oolitic limestones, with occasional beds of clay. They may be grouped as follows:

Upper Calcareous Grit and Upper Coral Rag . . . . Coral Rag and Coralline Oolite .	Upper Corallian.
Lower Calcareous Grit . .	Lower Corallian.

The deposits are very variable. Generally, however, the Lower Corallian consists of calcareous sandstone, forming the 'Lower Calcareous Grit.' The Upper Corallian consists chiefly of shelly limestones (the Coral Rag [1]), oolitic limestones (the Coralline Oolite), and sometimes the top beds are arenaceous, forming an 'Upper Calcareous Grit.' Over a considerable area in Wiltshire the upper beds have been converted into an oolitic ironstone, which was worked for many years at Westbury. At Wheatley, about five miles east of Oxford, the limestones somwhat suddenly disappear and the argillaceous facies begins.

Central District.—From the north-eastern part of Oxfordshire into Lincolnshire the Corallian series is represented for the most part by clay, known as the Ampthill Clay. In some places, for example at St. Ives in Huntingdonshire and Elsworth in Cambridgeshire, there is, at the base, a hard calcareous band with ferruginous oolitic grains. This band has now been traced for a considerable distance in Huntingdonshire and Cambridgeshire, and is generally called the Elsworth Rock, but it is a diachronic facies-deposit and not a true time-zone.

[1] The term 'rag' is used somewhat vaguely. It appears to be applied to any hard shelly or coralline limestone which breaks irregularly.

The Ampthill Clay is darker in colour than the Oxford Clay, and contains more carbonaceous material. It seems to represent only the Upper Corallian, and is slightly unconformable to the Oxford Clay.

At Upware, about nine miles north of Cambridge, there is a small isolated mass of Coral Rag and Coralline Oolite similar to the calcareous Corallian of the south of England, and containing a similar series of fossils. It represents a small coral reef, isolated in a muddy sea. A small boring has shown that at the base there is a hard band of calcareous ferruginous oolite like the Elsworth Rock.

Yorkshire.—In the southern part of Yorkshire the Corallian, if present at all, is of the argillaceous type; but in North Yorkshire the calcareous facies is again developed, and indeed attains a greater thickness than in any other district in England. It forms a large part of the hills round the Vale of Pickering.

The lithological subdivisions are:

Upper Calcareous Grit . .	Upper Corallian.
Coral Rag and Upper Limestone	
Middle Calcareous Grit . .	
Lower Limestone . . .	Lower Corallian.
Passage Beds	
Lower Calcareous Grit . .	

Essentially it consists of three arenaceous series, the Lower, Middle and Upper Calcareous Grits, separated by beds of limestone. There are, however, considerable variations in the development and thickness of these subdivisions.

Scotland.—No Jurassic deposits of later age than the Oxfordian series are found on the western side of Scotland. But on the eastern coast, in the Brora district, both the Corallian and the Kimmeridgian are present. The Corallian consists of limestones, clays and sandstones. Beds with marine fossils occur, especially at the base and towards the top, but the main mass of the series is a white sandstone with bands of lignite, and this is probably of estuarine origin.

The Kimmeridgian Series

The variable Corallian series is followed by the Kimmeridge Clay, or Kimmeridgian, one of the most constant and uniform formations in England. It is a dark grey or black shaly clay, which weathers brown upon its surface and often contains much selenite and pyrite. As a rule it is distinguished from the Oxford Clay by its darker colour and more shaly structure; also the layers of septaria are more frequent and more persistent. Occasionally the shales are highly bituminous and have been tried for oil, and sometimes there are bands of shaly limestone.

From Dorset to the Yorkshire coast the same lithological characters are preserved, and only the thickness varies. In the south of England

the Kimmeridge Clay is about 1,200 feet thick, in Oxfordshire about 100 feet, in Cambridgeshire 140 feet and in Yorkshire 400 feet, but the reduction in thickness in the Midlands is partly due to erosion.

In England the Kimmeridgian series was evidently deposited at a considerable distance from the shore. The sediment is always fine and without admixture of coarse material. But in the north of Scotland sands and grits and shelly limestones predominate.

Fossils are everywhere abundant. The dominant groups are those that flourish in a sea with a muddy bed. Corals and echinoderms are rare; gastropods are not very common. A few species of brachiopods are abundant, but the principal fossils are lamellibranchs and ammonites. *Aptychus* (the operculum of ammonites) is very common. Numerous remains of reptiles have been found, including *Ichthyosaurus*, *Plesiosaurus*, *Pliosaurus*, various Dinosaurs and other forms. Fish teeth, spines and scales are not uncommon. In spite of the carbonaceous character of some of the beds, plants are rare, except in Scotland.

Owing to the general uniformity of the deposits no lithological subdivisions can be traced, but a large number of zones have been established.

Amongst the common and characteristic fossils of the lower part besides ammonites, are *Ostrea deltoidea*, *Astarte supracorallina* and *Rhynchonella inconstans*. In the upper part *Orbiculoidea latissima* is very abundant in some beds. *Exogyra virgula* is also very common, but it extends downwards into the lower division.

On account of the overlap of the Cretaceous strata, the Kimmeridgian does not form so continuous a belt as the earlier series of the Jurassic system. In Bedfordshire, for example, the Cretaceous beds spread over it and pass on to the Oxford Clay.

Scotland.—The Kimmeridgian of the Brora district is an alternating series of sandstones, shales, limestones and grits. It is partly a marine and partly an estuarine deposit. Many of the Kimmeridgian ammonites and other fossils have been found in it, and there is also an abundant flora, including ferns, cycads and conifers.

The Portlandian Series

Unlike the preceding subdivisions of the Jurassic system, the Portland beds have a very limited distribution, at least upon the surface. This is due, in the south of England, chiefly to the unconformable overlap of the Upper Cretaceous; and beneath the surface the Portland series may perhaps be continuous from Dorsetshire into Buckinghamshire. But from Bedfordshire to Yorkshire no Portlandian beds are found, and there is no evidence that they exist below the Cretaceous covering.

The rocks of this series are best displayed in the south of Dorsetshire, especially in the Isles of Portland and Purbeck. Further north they

are exposed at intervals along the margin of the Cretaceous outcrop, where the Cretaceous escarpment has been cut sufficiently far back. This is the case in the Vale of Wardour; the Vale of Pewsey near Devizes; at Swindon; and near Oxford and Aylesbury. But beyond Leighton Buzzard the series is unknown.

Lithologically, the Portlandian consists chiefly of limestone and sands. It is a marine deposit, and fossils are abundant in the limestones, somewhat less common in the sands. Although calcareous rocks form so large a part of the series, neither corals nor echinoderms are particularly common. One species of coral, however, *Isastrea oblonga*, is occasionally found in considerable abundance, almost always in a silicified condition. Brachiopods are rare. Gastropods, lamellibranchs and ammonites, the latter of enormous size, are the principal fossils. In the limestones the shell has often been dissolved away, and only the mould and cast are left. *Cerithium portlandicum*, *Trigonia gibbosa* and *Perisphinctes giganteus* are three of the commonest and best-known forms.

In Dorsetshire the Portlandian falls naturally into two divisions, viz.:

2. Portland Stone or Upper Portlandian.
1. Portland Sand or Lower Portlandian.

The Portland Sand consists of yellow and greenish-grey sands with beds of loam and clay, and occasional layers of sandy or clayey limestone.

The Portland Stone consists chiefly of limestone, which may be shelly, oolitic, compact or chalky, with occasional sandy beds. Layers and nodules of chert are common in some of the limestones. It is from this series that the famous Portland building-stone is obtained.

In the Vale of Wardour the series retains the same general characters; but in the exposures further north the upper division, as well as the lower, is composed chiefly of arenaceous deposits. At Swindon, for example, the limestones are comparatively thin, and the principal member of the Upper Portlandian is a mass of buff and white false-bedded sands with bands and lenticular layers of calcareous sandstone.

The Purbeckian Series

In their distribution the Purbeck beds are closely connected with the Portlandian series. They are found in the south of Dorsetshire; in the Vale of Wardour; at Swindon, and in the neighbourhood of Oxford and Aylesbury. They do not appear in the Vale of Pewsey, but on the other hand they are exposed in the centre of the Wealden anticline, where the Portland beds do not reach the surface.

In general, the series rests conformably upon the Portlandian and passes up without a break into the Wealden beds above. But at Swindon there is a distinct unconformity between the Portland and

the Purbeck beds. Locally, irregular and eroded junctions occur in the midst of the Purbeck series itself, but probably none of these indicate any considerable lapse of time.

The Purbeck series consists chiefly of shales, marls and limestones. There are also occasional bands of dark loamy earth, which are known as Dirt-beds. By far the greater part of the series is of fresh or brackish water origin. The Dirt-beds contain tree-stumps and other terrestrial remains, and appear to be ancient soils. Only one band is definitely marine. This is the 'Cinder-bed,' which occurs in the midst of the series, and is made up almost entirely of the shells of *Ostrea distorta*.

The fauna of the series is very varied. Besides the shell already mentioned, *Hemicidaris purbeckensis* and other marine fossils occur in the Cinder-bed. In general, however, fresh-water, brackish-water and terrestrial animals and plants predominate. *Unio*, *Viviparus* (*Paludina*), *Physa* and *Limnaea* are abundant, especially in the upper beds. Ostracods, such as *Cypris* and *Cypridea*, occur throughout. The isopod *Archaeoniscus brodiei* is found in profusion in some localities. Insects of various kinds are numerous. Fish and reptiles are also often found. But perhaps the most remarkable of the fossils are the remains of mammalia which have been discovered at the base of the Middle Purbeck in Durlston Bay. These include *Plagiaulax*, *Triconodon*, *Spalacotherium* and several other genera.

Silicified remains of cycads and coniferous trees occur in the Dirt-beds, and some, at least, are in the position of growth.

The Purbeck series in its typical development is exposed in the south of Dorsetshire and in the Vale of Wardour. Further north, owing to the overlap of the Cretaceous, only the lower beds are seen. At Swindon, as well as near Oxford and Aylesbury, they consist of freshwater marls and limestones.

The upper part of the Purbeckian series is also exposed in the middle of the Wealden anticline in a band which runs from near Heathfield to the north of Battle. It consists chiefly of shales and limestones, with some bands of hard calcareous sandstone and of gypsum. These beds pass up conformably into the Wealden series. In the sub-Wealden boring near Battle the thickness of the gypsum deposits was very considerable.

There are no Purbeckian beds north of Buckinghamshire.

CHAPTER XXIII

THE CRETACEOUS SYSTEM

In the south of England sedimentation was continuous from the Jurassic to the Cretaceous, but over the greater part of the country there is more or less discontinuity and in one large area pronounced unconformity between the two systems. This is due to a phase of earth-movement which has until lately received little recognition in this country, the Saxonian or Cimmerian system of Continental geologists, which is of considerable importance in the location of buried coalfields in Belgium, Holland and western Germany. The extent of the disturbance in East Anglia and the southern Midlands is shown by the fact that in Bedfordshire the Lower Greensand rests on the Oxford Clay, all the intervening divisions having either been removed or never deposited. The strike of the Saxonian fold-lines is N.W.–S.E., and it is believed that some of their effects in England can be attributed to posthumous movements of old Charnian axes with the same strike. At any rate the centre of the pre-Cretaceous anticline of Jurassic rocks in Bedfordshire lies exactly on the prolongation of the axis of the Charnwood Forest anticline (see p. 309).

The Cretaceous beds (Fig. 120) form a broad band extending in an open curve from Flamborough Head to the Dorset coast, and, like the Jurassic beds, they have in general an easterly or south-easterly dip. But in the south of England the structure is complicated by a series of folds and faults which run from west to east. In consequence of these a broad arm of Cretaceous rocks spreads from the main band at Salisbury Plain to the shores of Sussex and Kent, and a narrower strip forms the southern rim of the Hampshire basin in the Isle of Purbeck and the Isle of Wight. Cretaceous rocks are also brought to the surface at one or two places in the midst of the Tertiary beds, both in the London and the Hampshire basins, as at Windsor and near Portsmouth.

Except where it is broken by the sea at the Wash, the main outcrop is practically continuous, and it is only in the south that there are neighbouring outliers of any considerable extent. But far away to the north-west, around the basaltic plateau of Antrim and beneath the lavas of Mull and Morvern, Cretaceous beds are again met with. They contain marine fossils, and prove that at one time the Cretaceous sea must have covered a great part of the British Isles. Both in Ireland

and in Scotland, however, much of the deposit is littoral in character, and some of the Scottish beds are estuarine.

In the main outcrop of the Cretaceous rocks the Chalk is always the

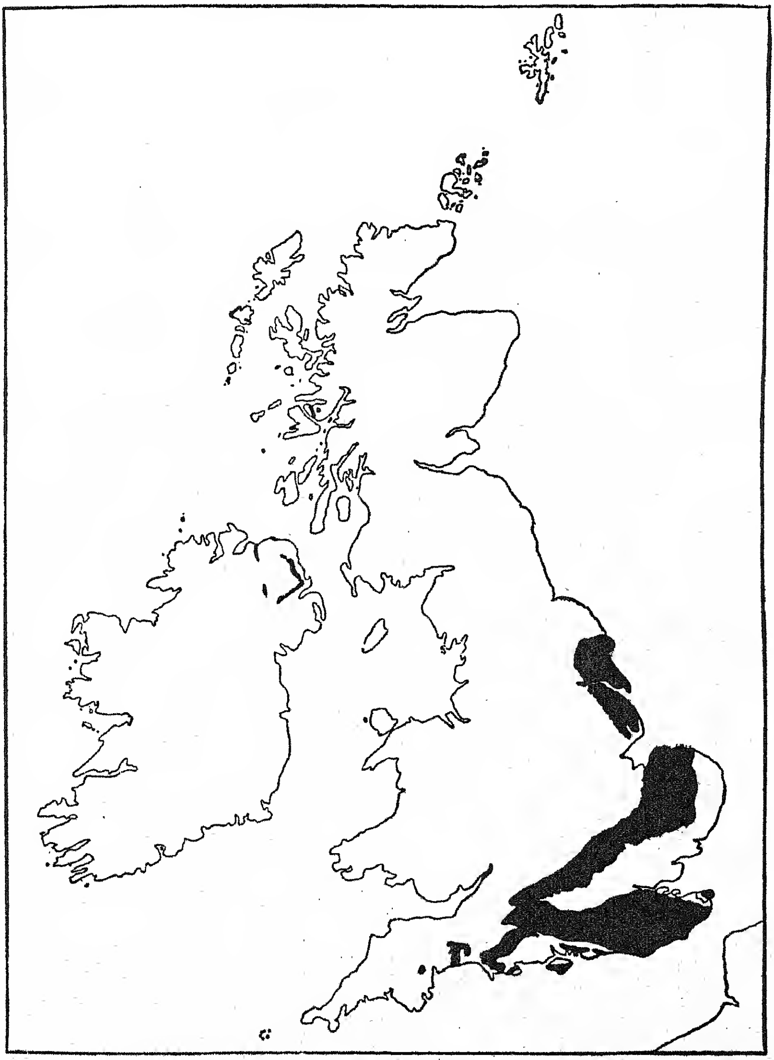


FIG. 120.—THE CRETACEOUS SYSTEM.

dominant member of the system, and everywhere it forms an undulating plateau which terminates westward in a well-defined escarpment overlooking the Jurassic or Triassic plains, while eastward it sinks gradually

beneath the Tertiary or later deposits. This escarpment is one of the most marked physical features of Eastern England, and is known under various names in different parts of the country. It forms the Yorkshire and Lincolnshire Wolds in the north, and the Gogmagog and Chiltern Hills further to the south.

In the easterly arm the lower beds play a more important part than in the main outcrop. The hilly region in the middle of the Weald consists of Lower Cretaceous rocks ; but the North and South Downs are formed by the Chalk.

The Cretaceous system falls naturally into two divisions, which differ widely in character and in distribution. The Lower Cretaceous consists chiefly of sands and clays, in part of fresh-water origin and in part marine. The Upper Cretaceous consists mainly of Chalk, but at its base is a variable series of clays and sands.

It is not, however, the difference in lithological character that constitutes the principal reason for separating the Lower from the Upper Cretaceous, but rather the difference in their distribution. The Lower Cretaceous is comparatively limited in extent. It is fully developed in the Weald, the Isle of Wight and the Isle of Purbeck ; but westward it is completely overlapped by the Upper Cretaceous, which here extends almost to the Carboniferous syncline of Devonshire. Towards the north, also, the overlap is almost equally marked, and throughout the greater part of the Cretaceous outcrop the Upper Cretaceous rests directly upon Jurassic rocks. The Lower Cretaceous, however, appears at intervals, but generally only the upper beds of that division. It is only in the north and south of England that the whole of the Lower Cretaceous is present.

In the distant exposures of Ireland and Scotland the Lower Cretaceous is altogether absent, and the Upper Cretaceous rests directly upon the older rocks.

In all directions, therefore, the Upper Cretaceous sea spread far beyond the margins of the Lower Cretaceous waters. And this is true not only of the British Isles, but also of a large part of the globe. Nearly everywhere the Upper Cretaceous extends beyond the limits of the Lower. Almost everywhere about this period the sea overflowed the shores of the ancient continents, and the ocean grew at the expense of the land. The overflow appears to have taken place almost simultaneously throughout the globe, and it is one of the most striking and widespread events in geological history. It is often called the 'Cenomanian Transgression,' but the transgression or overflow began before the Cenomanian epoch.

Microscopically, the Chalk consists chiefly of the tests of foraminifera, minute fragments of shells, especially of *Inoceramus*, and a matrix of very finely divided calcareous material. The proportion of these constituents varies greatly. In some cases the foraminifera or the

fragments of shells predominate, but in general the finer matrix forms the bulk of the rock. Sponge spicules are sometimes very numerous, and sometimes little globules of colloid silica abound. At one time it was supposed that the Chalk was originally a deep-water deposit, like the modern Globigerina ooze, but this idea is now generally abandoned. It is now generally held that the calcareous part was a chemical precipitate. At whatever depth the Chalk was formed, it was certainly laid down in a sea very free from detrital material. Either the water was deep, or the shore far away, or rivers brought little sediment from the land, the last being the most probable explanation. It has been suggested with much probability that the nearest land areas were desert.

It was, moreover, a sea of great extent, for the Upper Chalk spreads with little change of character from England to the east of Russia. But its width was comparatively small. In Scotland the deposits of the Chalk period are in part estuarine; in Saxony they consist chiefly of sandstone. The northern border of the sea seems to have stretched from Scotland to the south of Scandinavia; the southern border lay north of the Alps. The Chalk sea was therefore hardly comparable with the great oceans, but rather with the present Mediterranean.

Fauna and Flora.—So far as our islands are concerned, the flora of the Cretaceous is practically the flora of the fresh-water deposits at its base, for elsewhere remains of plants are rare. In the course of the Cretaceous period the vegetation of the world was transformed. Jurassic types continued with little or no break, including Ferns, Conifers, Cycads and Ginkgoaleans. But during the early part of the Cretaceous the flowering plants or Angiosperms, to-day the dominant group, became quite suddenly conspicuous in some parts of the world, and by the end of the Cretaceous the flora had changed literally from an ancient to a modern one.

The fauna of the Cretaceous period includes many of the genera that lived during Jurassic times, but it differs in many important respects. The difference is greatest in the case of the Chalk, partly, no doubt, because in point of time the Chalk is furthest removed from the Jurassic deposits; but partly also because it was laid down under very different conditions. Sponges are more abundant than in any other system. Calcareous forms are common in the Lower Greensand, the highest division of the Lower Cretaceous. In the Upper Cretaceous, siliceous forms predominate, especially in the Chalk; but calcareous forms are occasionally common in the Upper Greensand. In the British Cretaceous, corals are nowhere abundant, and they form no reefs or beds comparable with those of the Jurassic. A few simple corals, however, occur, such as *Trochocyathus*, *Parasmilia* and *Micrabacia*, and one or two compound forms such as *Holocystis*. Echinoderms, on the other

hand, are very common, especially in the Chalk. Echinoids predominate, and, indeed, this class attains its greatest development in the Upper Cretaceous. Amongst the most important genera are *Conulus*, *Micraster*, *Holaster* and *Echinocorys*. The crinoids are represented by *Marsupites* and a few other forms. Star-fish also occur. Brachiopods are not so numerous as in the Jurassic deposits. But *Terebratula* and *Rhynchonella* are still common, and other genera are also met with. Polyzoa are often found, both cyclostomatous and cheilostomatous forms being abundant. The Lamellibranchia are well represented. Fresh-water forms such as *Unio* and *Cyrena* occur in the Lower Cretaceous; but the special characteristic of the period is the abundance of *Inoceramus*, and (in Southern Europe) of the remarkable genus *Hippurites* and its allies. *Gervillia* and *Spondylus* are other genera which may be mentioned. Gastropods are common in some beds. Amongst them are the marine genera *Pleurotomaria* and *Aporrhais* and the fresh-water form *Viviparus*. Cephalopods are very abundant, especially ammonites and belemnites. The latter include the genus *Belemnites* itself, and also *Actinocamax* and *Belemnitella*. Amongst the ammonites are many of the normal type, but there is also a large variety of uncoiled or partly uncoiled forms such as *Hamites*, *Baculites*, *Scaphites*; this peculiarity was an indication of the approaching extinction of the race.

Fish remains are common, and the teeth of *Ptychodus* are well-known fossils from the Chalk. Reptiles are also found, *Iguanodon* being one of the most striking forms; the other groups of reptiles resemble those of the Jurassic system. A single genus of birds, *Enaliornis*, has been found in England; and other genera occur abroad. Many of them retain certain reptilian characters, such as the presence of teeth set in sockets. No mammalia are known in the English Cretaceous.

LOWER CRETACEOUS

In the south of England the Lower Cretaceous passes downwards without a break into the Jurassic and upwards into the Gault. The lower part is of fresh-water origin and is called the Wealden, the upper part is marine and is known as the Lower Greensand. Towards the north the higher beds overlap the lower, and consequently in the Vale of Wardour only the top of the Wealden series is present, and still further to the north the Lower Greensand rests directly and unconformably upon the Jurassic.

In Yorkshire and Lincolnshire both the Wealden and the Lower Greensand are represented by marine deposits: but again the higher beds overlap the lower—in this case towards the south—and accordingly

in Norfolk the lower beds are absent, and south of Ely the Lower Greensand rests directly upon the Jurassic.

Thus it appears that in the early part of the period the central district was land, separating a northern sea from a southern lagoon or estuary. Gradually the waters rose, and the deposits spread further and further over the central land until, in Lower Greensand times, the barrier was submerged. The sea, however, did not extend far to the north-west, as in several places the Lower Greensand is overlapped by the Gault. Even then, however, there remained a considerable difference between the northern and southern faunas and deposits.

According to the manner in which the Lower Cretaceous was laid down, England may therefore be divided into three districts: (1) a southern district, in which the Wealden series consists of fresh-water deposits; (2) a central district, in which the Wealden is altogether absent; and (3) a northern district, in which the Wealden is represented by marine deposits.

Owing to the overlap of the Upper Cretaceous, the boundaries of these three areas cannot be determined with precision. But the southern district extends as far north as the Vale of Wardour, where the last exposures of the Wealden fresh-water beds are seen; the central district stretches from Devizes to Ely; and the northern district includes Norfolk, Lincolnshire, and Yorkshire.

An important element controlling the deposition of the Lower Cretaceous is the platform of Palaeozoic rocks underlying the London basin. This relic of the Armorican ranges had by that time been worn down to a gently undulating land surface, and against it the New Red Sandstone and Jurassic strata ended off, with pronounced overlap. Throughout the Lower Cretaceous some land remained above sea-level, and the first Mesozoic marine formation to be found in all bores in south-eastern England is the Gault, indicating the onset of the Cenomanian Transgression. In many places the Palaeozoic rocks lie only a few hundred feet below present sea-level: in and around London and in east Kent at 1,000 to 1,400 feet; in Suffolk and Herts about 600 feet; and in Bucks only 150 feet.

In England the most remarkable of the Cretaceous deposits are the Greensands and the Chalk. Greensand is not by any means confined to this system. Chalky beds are also met with elsewhere, but in no other system do they approach in extent or thickness the Chalk of the Cretaceous.

The Greensands always owe their colour to the presence of grains of glauconite, but they vary considerably in composition and structure. One variety, known in England as malmstone and in France as gaize, consists principally of colloid silica with only a small proportion of grains of quartz and a very variable amount of glauconite. Other

varieties are true sandstones, made of grains of quartz and glauconite and flakes of mica, generally with a more or less calcareous cement. Still other beds are formed so largely of sponge spicules that they are really organic deposits rather than clastic sediments.

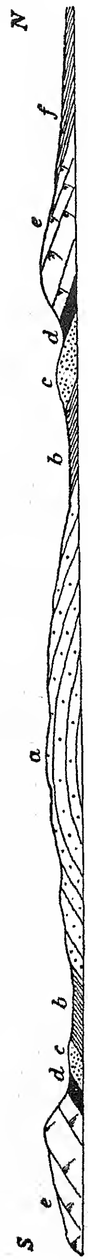


FIG. 121.—DIAGRAMMATIC SECTION ACROSS THE WEALD.
a, Hastings Sand; *b*, Weald Clay; *c*, Lower Greensand; *d*, Gault and Upper Greensand; *e*, Chalk; *f*, Tertiary.

At the present day glauconite may be formed at any depth down to 2,000 fathoms, or even beyond. Where the amount of terrigenous material is great, the proportion of glauconite is small; and the deposits in which the quantity of glauconite is sufficient to give a green colour to the whole occur mostly about the limit of wave and current action, especially at depths of 200 or 300 fathoms.

To the unaided eye the Chalk differs from other calcareous rocks in the purity of its colour, the absence of any visible crystalline structure and the extreme fineness of its particles. Chemically it is distinguished by the very small proportion of insoluble material. Frequently the residue after treatment with hydrochloric acid amounts to less than 2 per cent. But in the more marly beds it may rise to 15 or 20 per cent. Towards the base the quantity increases, and it becomes obvious even to the eye that the Chalk is no longer pure. The insoluble residue consists chiefly of detrital material derived from the land; and in the south of England it is noticeable that the proportion increases gradually from Kent to Dorset.

SOUTHERN DISTRICT

In the south of England the Lower Cretaceous forms the central portion of the dome of the Weald, occupying almost the whole of the area between the North and South Downs (Fig. 121). Another anticlinal fold brings it again to the surface in the Isle of Wight, of which it forms the southern half; and owing to the same fold it crops out in a narrow band from east to west across the Isle of Purbeck. A few small inliers occur along another anticlinal axis about six miles north of Weymouth. Both towards the west and towards the north it is overlapped by the Upper Cretaceous; but it reappears in the Vale of Wardour, where the Chalk escarpment has been cut back far to the east of its general direction.

Here, however, the outcrop is narrow, and but little of the fresh-water series is visible.

Throughout this district the Wealden series is represented by fresh-water deposits, and the Lower Greensand is marine. In the Weald both series thicken from east to west; but they appear to attain their maximum about the longitude of the Isle of Wight, and in Dorsetshire they begin to thin in a westerly direction.

In the Isle of Wight the base is not visible, but in the Weald and the Isle of Purbeck the Wealden passes without the slightest break into the Purbeck beds below, and the boundary between the two series is purely artificial. Similarly, there is no very sharp line between the Lower Greensand and the Gault above. But the boundary between the Wealden and the Greensand is always clear and well defined, and is often marked by a line of pebbles or of coarse grit. There is, however, no proof of unconformity, and the boundary is such as might be expected if the sea invaded an area already covered by fresh water.

In the Vale of Wardour, which lies near the margin of the old lagoon, the lower part of the Wealden series is absent and the upper beds rest unconformably upon the Purbeck.

The Weald is the largest area of Lower Cretaceous rocks in England, and may accordingly be taken as the type of the southern development. The subdivisions there recognised are as follows:

Lower Greensand		Folkestone beds. Sandgate beds. Hythe beds. Atherfield Clay.
Wealden	Weald Clay.	
	Hastings Sand . .	Tunbridge Wells Sand. Wadhurst Clay. Ashdown Sand.

The subdivisions in the first and second columns can generally be recognised over the whole of the southern district; the minor subdivisions in the third column cannot be clearly distinguished except in the Weald.

Wealden Series.—The Hastings Sand forms the hilly ground in the middle of the Weald, rising at Crowborough Beacon to a height of nearly 800 feet. It consists chiefly of light-coloured sands or soft sandstone with variable and subordinate bands of clay. But towards the middle there is a very constant bed of clay, 100 to 150 feet in thickness, called the Wadhurst Clay, which separates the Ashdown Sand below from the Tunbridge Wells Sand above. Close to the base of the Wadhurst Clay there are nodules and bands of ironstone, which in early days were the principal source of iron in Great Britain. In some parts of the Weald other beds of clay attain a considerable thickness. Near Hastings and Fairlight, for example, the lower part of the Wealden

becomes so argillaceous that it is often separated as a special subdivision under the name of the Fairlight Clays; but the Fairlight Clays are contemporaneous with the lower part of the Ashdown Sand of other districts.

As a rule fossils are not common in the sandy beds, but remains of plants and reptiles occur. The Fairlight Clays have yielded a large number of plants, mainly cycads, ferns and conifers of Jurassic type. The Wadhurst Clay is very fossiliferous. *Viviparus fluviorum* and *Cyrena media* are here the principal shells. *Lepidotus mantelli* and other fish, *Iguanodon* and other reptiles, are also abundant.

The Weald Clay forms the broad depression which surrounds the central hilly region of the Weald and separates it from the Downs. It consists chiefly of brown, blue or yellow clay, but includes layers of shelly limestone often hard enough to take a good polish and known under various local names, such as the 'Bethersden marble.' There are also occasional beds of sandstone. *Viviparus fluviorum* and *V. sussexensis* are the commonest shells, but fresh-water lamellibranchs such as *Unio* and *Cyrena* also occur, and small ostracod crustaceans such as *Cypridea* are often very abundant. Remains of reptiles and plants are also found in the clay.

When traced from the Weald towards the west, the Wealden series shows certain changes. In the Isle of Wight the Hastings Sand does not reach the surface; but the Weald Clay is fairly exposed in the northern part of Sandown Bay on the eastern coast, and on the western coast is well exhibited in the cliffs between Compton Bay and Atherfield. A striking feature is the 'pine-raft' near Brook Chine. This is a collection of coniferous trunks which were evidently washed down into the Wealden delta and there became water-logged and sank.

In the Isle of Purbeck the whole of the Wealden series is exposed to view. It thins towards the west, and as it thins the sediment grows coarser, the clays giving place to sands, and the sands to pebbly grits. Three small inliers lie to the north of Weymouth, the most westerly being that of Ridgeway.

Lower Greensand.—The Lower Greensand is harder than the Weald Clay below and the Gault above, and consequently it forms a prominent ridge in front of the main escarpment of the Downs, including the heights of Hindhead, Leith Hill, etc.

It is a variable series of sands and clays, often, but by no means always, full of glauconitic grains. Some of the beds are highly calcareous, and under the name of 'Kentish Rag' are used for building and are burnt for lime.

The subdivisions recognised in the Weald may be briefly described as follows:

4. Folkestone beds	.	Chiefly sandy, sometimes with hard cherty beds made up largely of sponge spicules, sometimes with irregular layers of ironstone.
3. Sandgate beds	.	Generally more or less argillaceous, but with a good deal of sand and sandy clay. Fuller's earth occurs in some districts.
2. Hythe beds .	.	Sands and limestone. Includes most of the 'Kentish Rag.'
1. Atherfield beds	.	Chiefly brown clay.

These divisions, however, are purely lithological and have no palaeontological basis. They are therefore only of local value. The Atherfield Clay retains the same general character in the Isle of Wight and the Isle of Purbeck; but the Sandgate beds cannot be definitely distinguished. In general, the Lower Greensand of the south of England may be divided into a lower argillaceous stage, the Atherfield Clay, and an upper arenaceous stage, including the rest of the series.

Amongst the more common and characteristic fossils of the Lower Greensand are *Peltastes wrighti*, *Meyeria magna*, *Terebratula sella*, *Exogyra sinuata*, *Perna mulleti*, *Gervillia sublanceolata*, *Parahoplitoides deshayesi*.

Central District

In the middle of England the Lower Greensand appears at intervals along the Cretaceous outcrop from Devizes to Ely; but it rests directly and unconformably upon the Jurassic beds below, and there is no trace of the Wealden except at Shotover near Oxford and Brill in Bucks. Its base is often pebbly, and in Bedfordshire and Cambridgeshire is frequently full of coprolites or phosphatic nodules, which were formerly extensively worked for manure. The greater part of the series consists of sands, often quite soft and loose, white, yellow or brown at the surface, but in deep wells and bores the darker varieties are of a dull green colour, from unoxidised glauconite: current-bedding is often conspicuous. Some bands are much hardened by iron oxides, often showing box-stone structure, while other bands are cemented by calcite. There are also occasional beds of clay.

It is not possible to distinguish the local subdivisions recognised in the south of England. Near Faringdon in Berkshire is a remarkable deposit of gravel formed very largely of sponges.

When followed northwards the Lower Greensand appears rather suddenly in strong force at Leighton Buzzard in Bedfordshire, where it consists of silvery white sand suitable for glass-making. At Woburn there are 220 feet of yellow sands with a bed of fuller's earth and there is a fine exposure of yellow sands alongside the main line of the L.N.E.R. at Sandy station. In Cambridgeshire the outcrop is narrow, but the light, well-drained soil has given rise to an important fruit-growing industry. (This has now spread to several other geological formations.)

The Lower Greensand, here often hardened by a calcite cement, forms the capping of the Isle of Ely and several other ' islands ' in the Fens. When the series reappears in Norfolk it is more complicated and thicker. The Sandringham Sand at the base, also a good glass sand, is on a lower horizon than is known in southern England in the marine facies (Neocomian of the continental classification). The Snettisham Clay above is poorly exposed and not much is known about it, but the upper division, the Carstone, is well seen in the cliff at Hunstanton and in several quarries. It is a dark yellow or brown highly ferruginous sandstone or grit, often pebbly or almost conglomeratic, with strongly marked rectangular jointing and box-stone casings. It affords a very good building stone. Throughout the whole series fossils are scarce, and the correlation with other areas is rather uncertain.

For the Lower Greensand of the Cambridge district as a typical example of semi-artesian water supply, see page 78.

Northern District

The Lower Cretaceous of Yorkshire and Lincolnshire differs so much from that of Southern England that no exact correlation of the strata is yet possible. Palaeontologically, indeed, these northern deposits are much more closely connected with those of Russia. They contain many species found in that country but unknown in the south of England and in France. Apparently the sea which covered Northern Russia extended into the north-east of England. When, however the land area of Central England and the fresh waters of the Weald were invaded by the sea, it was not the fauna of the northern sea that crept over the area, but the fauna of a sea which lay to the south of England, and many of these southern forms spread for a time into the waters of the northern sea.

It is in the neighbourhood of Speeton, north of Flamborough Head, that the most definite palaeontological sequence has been made out; and consequently the Speeton beds may be taken as the type of the northern development.

The deposits here consist almost entirely of clay or shale, which is for the most part dark in colour. They rest directly on the Kimmeridge Clay and the only sign of erosion is a bed of phosphatised nodules at the base, with derived Kimmeridgian ammonites, although the Portland and Purbeck beds are absent: a striking example of non-sequence. Belemnites are by far the most abundant and characteristic fossils, but ammonites and other forms occur. One band has yielded a considerable number of the sea-urchin *Echinospatagus cordiformis*. By means of the Belemnites the whole series may be divided as follows:

5. Zone of *Belemnites minimus* (base of Upper Cretaceous).
4. ,, ,, *brunsvicensis.*
3. ,, ,, *jaculum.*
2. ,, ,, *lateralis.*
1. Coprolite bed.

The coprolite bed is a thin seam of black phosphatised nodules, only about four inches thick. Its fossils are poorly preserved, and most of them seem to have been derived from lower beds. *Belemnites lateralis* is a short, thick species common in Russia. It is rare in the south, but one or two specimens have been found in the Portlandian of Boulogne. *B. jaculum* is a long and slender form which occurs in France, Germany and the Alps. *B. brunsvicensis* is believed to be a descendant from some form allied to *B. lateralis*, and is found in Russia and Germany, but not in the southern Cretaceous. On the whole, the fauna of the *B. lateralis* zone is very distinct from that of the south, while the faunas of the two succeeding zones show a mixture of northern and southern forms.

Because the Speeton Clays are marine and the corresponding beds of Southern England are in part of fresh-water origin, direct comparison is very difficult. *B. minimus* is a common Gault fossil, and its zone probably represents the base of the Upper Cretaceous. The zone of *B. brunsvicensis* contains *Parahoplitoides deshayesi* and other fossils which show that it represents in part the Lower Greensand, but it is quite possible that the *B. jaculum* zone may also belong in part to that series. There is no evident gap between the Speeton series and the Kimmeridge Clay below, but the seam of phosphatic nodules at its base indicates a pause in deposition. Apart from the derived Kimmeridgian ammonites in this seam the ammonite fauna of the Speeton series is entirely Cretaceous. The Portlandian, Purbeckian, and even the lower zones of the Cretaceous are absent.

The Speeton Clay is overlapped to the west and south by the Upper Cretaceous; but Lower Cretaceous beds reappear in Lincolnshire. Here they are formed of coarser sediments than at Speeton, and include beds of sandstone and limestone. The limestone is sometimes partly replaced by ironstone. The same zones can be recognised as in Yorkshire, and the deposits were evidently laid down in the same sea but nearer to its southern margin. The following divisions are recognised

Carstone . . (in part)		Zone of	*B. minimus* (Upper Cretaceous).
Tealby Limestone and Roach Ironstone	. =	,,	*B. brunsvicensis.*
Tealby Clay . . .	=	,,	*B. jaculum.*
Claxby Ironstone Spilsby Sandstone	. . =	,,	*B. lateralis.*

At the base of the Spilsby Sandstone is a bed of phosphatic nodules. Several Lower Greensand forms, such as *Exogyra sinuata* and *Perna mulleti*, have been recorded from the Tealby Clay, and several occur

also in the Tealby Limestone. The Carstone is a pebbly ferruginous sand or sandstone containing very few fossils except at the top, where the Gault species *B. minimus* and *Terebratula biplicata* are found. One or two Lower Greensand species occur at the base, where phosphatic nodules are also found. Possibly they may have been derived from the destruction of an older stratum.

UPPER CRETACEOUS

As already explained (p. 416) the most notable feature of the Upper Cretaceous in many parts of the world was a widespread transgression of the sea over areas that had lately been land and a consequent deepening of the water over the shallow tracts. Therefore the Upper Cretaceous is much more uniform than the Lower. Lithologically it may be divided into an argillaceous and arenaceous series below, and a calcareous series above. The first is the Gault and Upper Greensand; the second is the Chalk.

The Upper Cretaceous is divided into a number of zones by means of fossils as given below. It will be noticed that these are not all named after ammonites, as in the Jurassic, since this group began to get scarce in the Chalk, and to a great extent sea-urchins took their place, while belemnites, brachiopods and lamellibranchs are also used as zone-fossils.

Upper Chalk	Zone of *Ostrea lunata*	Senonian.
	" *Belemnitella mucronata*	
	" *Actinocamax quadratus*	
	" *Marsupites testudinarius*	
	" *Micraster cor-anguinum*	
	" " *cor-testudinarium*	
	" *Holaster planus*	Turonian.
Middle Chalk	" *Terebratulina lata*	
	" *Rhynchonella cuvieri*	
Lower Chalk	" *Holaster subglobosus*	Cenomanian.
	" *Schloenbachia varians*	
Upper Greensand and Gault	" *Pecten asper*	Albian.
	" *Mortoniceras rostratum*	
	" *Hoplites lautus*	
	" *Hoplites interruptus*	
	" *Douvilleiceras mammillatum*	

Still higher beds appear upon the Continent and are known as Danian.

The names in the left-hand column are based on the lithological nature of the beds in England. Those in the right-hand column are of French origin and have no lithological significance. They are intended for universal application, and can be used even when the character of the deposits is entirely different, provided that the correlation can be determined by fossils. The zone of *Holaster planus*, the Chalk Rock (see later) is purposely left in an indeterminate position

between the Middle and Upper Chalk, since authorities differ on its allocation to one or the other.

The modern zoning of the Gault has become so complicated that the rather old-fashioned list given above is here retained, as being useful in practice.

Besides the zone fossils, the Gault and Upper Greensand include many other characteristic forms. Amongst the commonest are *Terebratula biplicata*, *Inoceramus sulcatus*, *I. concentricus* and *Belemnites minimus*.

The Chalk also contains a very large number of well-known species, such as *Siphonia königi*, *Conulus conicus*, *Echinocorys* (*Ananchytes*) *vulgaris*, *Spondylus spinosus*, *Inoceramus mytiloides*.

There is no longer the marked difference between the deposits of the south and of the north of England that existed in Lower Cretaceous times, for both areas were covered by the same sea. But still a difference remains, especially in the lower beds. The Gault and Upper Greensand of the south are represented further north by a thin bed of red chalk, which lies beneath the ordinary white chalk.

Accordingly England may still be divided into a northern and a southern district; and for convenience of description a central district may also be distinguished.

Southern District

This area may be taken to include England south of the Thames but it cannot be sharply separated from the Central District.

Gault and Upper Greensand.—The Albian of Continental writers is represented by the Gault, sometimes with and sometimes without the Upper Greensand above. Palaeontologically, the topmost part of the Lower Greensand should be included, for it is here that the change of fauna begins.

No line can be drawn between the Upper Greensand and the Gault, for the former is only a sandy facies of the latter, and the beds which are sandy in one locality are represented by clay in others. The series is divided into five zones, in descending order—

5.	Zone of	*Pecten asper*	Sand.
4.	,,	*Mortoniceras rostratum* . .	Clay or sand.
3.	,,	*Hoplites lautus*	Clay.
2.	,,	*Hoplites interruptus*	Clay.
1.	,,	*Douvilleiceras mammillatum* . .	Sand

The first of these zones is always sandy, and is sometimes included in the Lower Greensand, which it resembles lithologically.

The next two zones always consist of clay. The *rostratum* zone is sometimes sandy and sometimes clayey; and the zone of *Pecten asper*, when it is present, is always sand. The clay is called the Gault and the sand is called the Upper Greensand.

At Folkestone no Upper Greensand is present, and the Chalk rests directly on the Gault. It is only in the extreme west of Kent, near the village of Westerham, that the Upper Greensand begins to appear. Through Hampshire and the Isle of Wight the sandy facies spreads downwards, and in Dorsetshire the whole of the two upper zones is formed of sandy beds. Still further west the series passes over the Jurassic and older rocks, and the higher beds overlap the lower, so that in West Dorset and in Devon the sandy beds representing the *rostratum* and *Pecten asper* zones rest directly upon the older rocks, without any bed of clay beneath.

The Chalk.—The Gault and Upper Greensand are followed by the Chalk, which forms the North and South Downs, Salisbury Plain and its south-westerly continuation, and also the axes of the Isle of Wight and the Isle of Purbeck.

The Chalk is by no means constant either in composition or texture, but the general appearance of the deposit is remarkably uniform, and the lithological variations are far from conspicuous to the eye. Often, indeed, no trace of bedding is visible, and often the stratification is revealed only by lines of flints. But careful examination shows that sometimes the Chalk is soft and marly, sometimes it is hard and lumpy; sometimes it contains numerous rows of flints, sometimes few or none. Seams of phosphatic nodules occur at certain horizons, and grains of glauconite are abundant at others.

It is accordingly possible to distinguish definite lithological subdivisions, and some of these are remarkably constant in character over wide areas. In the south of England the following divisions can usually be recognised:

		Zones.
Upper Chalk	White chalk, usually with many flints; more or less nodular towards the base	*Belemnitella mucronata* to *Holaster planus*.
Middle Chalk	Soft white chalk, with occasional beds of marl, usually with few flints	*Terebratulina lata*.
	Hard nodular chalk, Melbourn Rock	*Rhynchonella cuvieri*.
Lower Chalk	Thin bed of marl (Belemnite Marl) Massive white chalk	*Holaster subglobosus*.
	Grey chalk Chalk Marl, with chloritic marl at base	*Schloenbachia varians*.

As the Upper Chalk is thicker than all the other divisions of the Upper Cretaceous put together, with a maximum of 1,150 feet in Norfolk, it occupies the greater part of the area coloured as Chalk on geological maps.

The lithological divisions do not always correspond precisely with the zones.

The base is usually glauconitic and often sandy, and is commonly distinguished by the name of Chloritic Marl. This is followed by soft grey marly chalk, graduating upwards into a more solid chalk which is still grey in colour. These subdivisions together constitute the zone of *Schloenbachia varians*.

The grey chalk is succeeded by massive white chalk, with *Holaster subglobosus*, etc., and at the top of this is a thin but very constant band of soft marl containing *Actinocamax plenus* in abundance. This is often known as the Belemnite Marl or the sub-zone of *A. plenus*. It forms the upper limit of the Lower Chalk.

The Middle Chalk begins with a hard nodular band, called the Melbourn Rock, and this is followed by a soft white chalk with occasional beds of marl and usually with few flints. The Melbourn Rock and a part of the softer chalk above belong to the *Rhynchonella cuvieri* zone; the rest of the Middle Chalk to the zone of *Terebratulina lata*.

The Upper Chalk is usually white and pure, but seams of marl occur in places, and nodular and lumpy beds are often found towards the base. In the south of England it is usually distinguished by the abundance of flints. Formerly, in fact, it was called the Chalk with Flints, and the Lower and Middle divisions were known as the Chalk without Flints; but this distinction cannot be maintained. The *Marsupites* zone contains comparatively few flints, while towards the west flints become abundant in the Middle Chalk. The Upper Chalk is characterised by the great abundance of *Micrasters* in the lower zones, and of belemnites (*Belemnitella* and *Actinocamax*) towards the top.

Towards the west the character of the Chalk gradually changes. In Devonshire the lower part beomes a calcareous sandstone overlaid by a bed of hard quartziferous limestone. It was evidently deposited upon the margin of the Cretaceous sea. The Middle Chalk is hard and gritty at its base, while higher up it is a chalk with many flints. On this account it was formerly referred to the Upper Chalk, but the fossils are those of the *Terebratulina lata* zone. The true Upper Chalk includes the zones of *Holaster planus* and *Micraster cor-testudinarium*, and retains its chalky character. The higher zones have been removed by denudation.

Central District

The Central District may be considered to extend as far north as the south of Norfolk.

Gault and Upper Greensand.—The Albian retains the same general characters as in the south of England. About Devizes and the Vale of Pewsey the Upper Greensand is well developed and forms the zones

FIG. 122.—DIAGRAMMATIC SECTION FROM ST. IVES THROUGH CAMBRIDGE TO BALSHAM.

a, Oxford Clay; *b*, Elsworth Rock; *c*, Ampthill Clay; *d*, Kimmeridge Clay; *e*, Lower Greensand; *f*, Gault; *g*, Chalk Marl with Cambridge Greensand at base; *h*, Totternhoe Stone; *i*, Lower Chalk; *j*, Melbourn Rock; *k*, Middle Chalk; *l*, Chalk Rock; *m*, Upper Chalk.

of *Pecten asper* and *Mortoniceras rostratum*. But towards the north the sandy beds are gradually replaced by clay, and the Upper Greensand finally disappears in Bedfordshire. In Cambridgeshire the upper part of the Gault was eroded before the deposition of the Chalk. Its upper surface is accordingly uneven, and the *rostratum* zone in some places appears to have been completely worn away. The erosion was due, not to elevation above the surface of the water, but rather to the action of currents upon the floor of the sea. At Cambridge the Gault is 150 feet thick and a maximum of 242 feet has been recorded in a bore at Newmarket.

The Chalk.—The Chalk of the Central District may be divided as shown on p. 431.

The lithological divisions do not correspond exactly with the zones.

As in the south of England, the *varians* zone consists chiefly of marly chalk, and is known as the Chalk Marl. In Bedfordshire and Cambridgeshire it rests upon an eroded surface of the Gault, and at its base is a sandy or pebbly bed containing coprolites and including many phosphatised Gault fossils. This deposit is commonly known as the Cambridge Greensand; but it is a part of the Chalk Marl, and the Gault fossils which it contains have been washed out from the upper part of that formation.

Lithological Divisions.		Zones.
Upper Chalk . .	Chalk with many flints . .	*Micraster* zones.
	Chalk Rock	*Holaster planus.*
Middle Chalk . .	Chalk with few flints . . .	*Terebratulina lata.*
	Melbourn Rock	*Rhynchonella cuvieri.*
Lower Chalk. .	Belemnite Marl . . . . Chalk without flints . . . Totternhoe Stone	*Holaster subglobosus.*
	Chalk Marl (with Cambridge Greensand at its base) . .	*Schloenbachia varians.*

The remainder of the series consists chiefly of normal chalk; but it is divided by three bands of harder chalk, which can be traced over most of the area, and serve as convenient guides in delimiting the principal subdivisions.

The lowest of these hard bands is the Totternhoe Stone, which rests upon the Chalk Marl and forms the base of the *Holaster subglobosus* zone; the second is the Melbourn Rock at the bottom of the Middle Chalk; and the third is the Chalk Rock, which lies at the base of the Upper Chalk.

Over most of the Central District the whole of the Chalk above the *Micraster* zones has been removed by denudation. But higher beds appear to be present at Taplow, near Maidenhead, and at Needham Market, in Suffolk.

The Chalk Marl is the basis of a highly important Portland cement manufacture at and near Cambridge.

Northern District

This extends from Norfolk to Flamborough Head in Yorkshire. Under the Fenland the Gault thins northwards, and in West Norfolk it is condensed to 4 feet in the Hunstanton Red Rock. This consists mainly of a finely divided chemical precipitate of calcium carbonate, coloured bright red by finely divided ferric oxide. It contains some sand and small pebbles, often highly polished, and a good many fossils; Lower Gault forms in the lowest foot and Upper Gault forms above. It was laid down in an area of shallow water with little access of land-derived material except the iron oxide, which may have come from a region of lateritic weathering (see p. 88). It is often called the Red Chalk, but this is undesirable, since it does not represent any part of the true Chalk, but is wholly of Gault age (Albian).

Across the Wash in Lincolnshire the Red Rock reappears, but it is thicker, up to 12 feet, and paler in colour, being less condensed. It is continued into Yorkshire, but at the northern end of the outcrop near Speeton the series thickens and consists of marls and clays, for the most part red.

The Chalk.—The Lower Chalk is generally thinner than in the south, and it is no longer argillaceous towards its base. There is, in fact, no true Chalk Marl, and the *varians* zone consists of hard white or grey chalk. The Totternhoe Stone is only about two feet thick, but may still be traced throughout the region. The Belemnite marls at the top of the Lower Chalk are present in Lincolnshire and Yorkshire. In some places the Lower Chalk includes red and purple bands.

The Middle Chalk is also thin, and unlike the corresponding beds of Central and South-eastern England, it often contains many lines of flints. The Melbourn Rock ceases to be distinguishable in Lincolnshire; but in Yorkshire practically the whole of the Middle Chalk is hard.

In contrast with the lower and middle divisions the Upper Chalk of the northern district appears to be considerably thicker than in the south of England. In Norfolk it is estimated to attain a thickness of 1,150 feet, and it includes higher beds than any which are known elsewhere in England. These topmost beds form the zone of *Ostrea lunata*, and are found only at Trimingham, east of Cromer.

In Lincolnshire the Chalk above the *Micraster* zones has been denuded. But in Yorkshire the *Marsupites* and *Actinocamax quadratus* zones reappear, and are both entirely destitute of flints.

Ireland

In the north-east of Ireland Cretaceous rocks appear at intervals around the borders of the basaltic plateau of Antrim, and bear witness to the extension of the Cretaceous sea in this direction. They rest unconformably upon Triassic and Liassic beds, and the nature of the deposits shows that they were laid down near the shore. Although they belong entirely to the Upper Cretaceous, they appear to form two distinct series separated by an unconformity.

The Lower series consists of marls and sandstones, glauconitic at the base and towards the top. They contain *Exogyra laevigata*, *Pecten asper*, *Schloenbachia varians*, etc., and appear to represent a part of the Lower Chalk of England, and perhaps the top of the Upper Greensand. It is possible, however, that owing to the sandy nature of the deposit some of the Upper Greensand forms may have survived into the period of the Lower Chalk.

The Upper series is formed chiefly of hard chalk, with rows of flints, and is generally glauconitic towards its base. In the eastern part of the area it passes downwards into glauconitic sands, not unlike those at the top of the lower series. But these sands contain *Echinocorys*

gibbus, *Micraster* and *Conulus*, together with numerous fragments of *Inoceramus*, and clearly belong to the Upper Chalk. The chalk above appears to represent the Upper Chalk from the zone of *Micraster cor-anguinum* to the zone of *Belemnitella mucronata.* The greater part belongs to the latter zone.

Scotland

In Scotland, as in Ireland, Upper Cretaceous rocks have been found below Tertiary basalts in Mull and Morvern. They rest unconformably on Lias and older rocks and show strong evidence of the prevalence of desert conditions on the neighbouring land. The whole series is very thin, only about 70 feet at the most. The lowest division, which is lithologically a greensand, belongs to the Cenomanian, as shown by its fossils: the Turonian is absent; while the upper division includes the zone of *Belemnitella mucronata*, of the highest Senonian.

CHAPTER XXIV

THE EOCENE AND OLIGOCENE SERIES

The most striking characteristics of the British Tertiary sediments might almost be described as negative: that is to say, their limited distribution and small thickness where they do occur. The reason for the limited distribution is that most of the area was land, and where the sea did exist it was very shallow. In the London basin the Eocene barely adds up to 900 feet at the most, whereas in Iran and Iraq, for example, it has a maximum thickness of 10,000 feet and the other divisions are also measurable by tens of thousands of feet. It is of interest to note that the equivalents of beds not represented at all in Britain yield a very large proportion of the oil production of the world. The absence of the Miocene and parts of the Oligocene and Pliocene is the result of the Alpine orogeny and revolution and the great igneous activity of Eocene times in north-western Britain (see Chapter XXVIII) is another phase of the same events. But it cannot be too strongly emphasised that the study of the British Tertiary beds alone gives a very imperfect impression of world-history during that period. It was then that the Alps and the Himalayas were formed; the Andes, the Rocky Mountains, and the island arcs of Asia took on their present form; and as a comparatively minor point, the British Isles became very much as they are now. From the point of view of modern world geography the Middle Tertiary was the most important of all periods, although in the geology of most of Britain there is hardly any record of it. In the south of England, however, the effects of the Alpine earth-movements are traceable in the present distribution of the Cretaceous rocks and the separation of the Eocene into two distinct basins by the Wealden uplift, which is of Miocene age, as well as the remarkable structure of the Isle of Wight. The development of the drainage systems of the country has been discussed in Chapter III.

Everywhere in Northern Europe the upper limit of the Chalk is marked by a sudden and striking change of fauna. Not only do species and genera disappear, but whole groups of animals die out and new types come in. In England the break is complete, and if we except such lowly forms as the Foraminifera, not a single species passes from the Cretaceous to the Tertiary. The change takes place at an unconformity, and the uppermost beds of the Cretaceous were removed before the Tertiary deposits were laid down; and thus the change of fauna is in part explained. At a few localities in France, Belgium

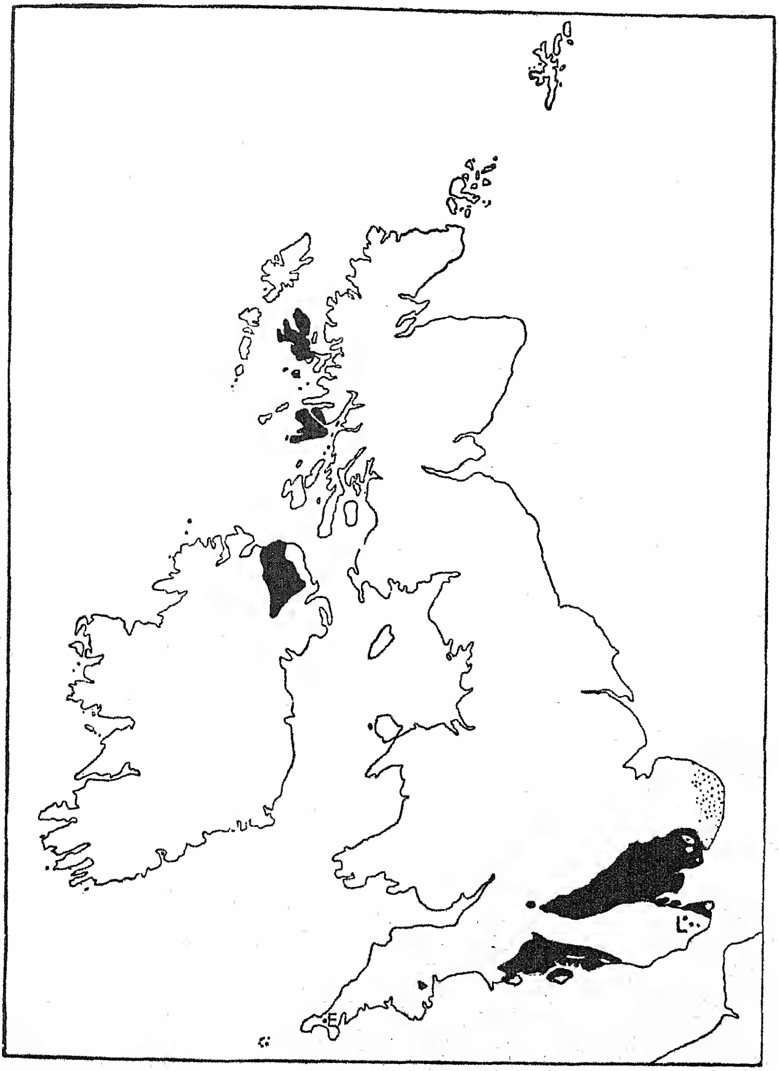


FIG. 123.—THE TERTIARY ROCKS OF BRITAIN.

Eocene and Oligocene, black. Pliocene, stippled. L = Lenham Beds.
E = St. Erth.

and Denmark, some of the missing beds are seen, and in these there is a certain mixture of Tertiary and Cretaceous species. But even here the gap is not by any means completely filled.

The change in fauna was not due entirely to lapse of time. It was in part the result of a complete alteration of conditions. Instead of the clear waters in which the Chalk was formed, there was a muddy sea into which large rivers poured a vast amount of land-derived material. The ammonites, belemnites, and sea-urchins of the Chalk accordingly disappeared and their place was taken by animals, adapted to such a habitat.

It is on account of this very abrupt change both in the fauna and in the character of the deposits that the line between the Mesozoic and Kainozoic rocks is placed at the top of the Chalk. But when we extend our view to other quarters of the globe, the boundary becomes less definite, and in some regions there is a perfect passage from the one set of deposits to the other.

In England the Tertiary beds fall naturally into two groups separated by a considerable interval of time, and when they occur together, by a decided unconformity. But the unconformity is local and in some parts of the Continent the succession is complete. The main divisions usually recognised are as follows:

Upper Tertiary or Neogene	Pleistocene. Pliocene. Miocene.
Lower Tertiary or Palaeogene . . .	Oligocene. Eocene.

The five smaller divisions are sometimes known as systems, but it is doubtful whether the whole of the Tertiary occupied as much time as even some of the series of the Palaeozoic. As, however, the various systems and series of stratigraphy are of very unequal value, the question of terminology is of little importance.

THE EOCENE

The Eocene beds of England (Fig.123) occupy two large triangular areas on either side of the Wealden anticline. On the north lies the London Basin, and on the south the Hampshire Basin. Beyond the limits of these two great basins a number of small outliers rest upon the Chalk of Salisbury Plain, the Chiltern Hills, etc., and seem to indicate that the Eocene deposits once covered the whole of South-eastern England. Moreover, the close similarity, in fauna and in lithological sequence, between the London and the Hampshire Basins shows that the same sea spread over both. The Eocene beds are themselves involved in the Wealden anticline, which must therefore be of post-Eocene date; and hence we may conclude that the London and

Hampshire Basins were originally continuous, and owe their separation to the subsequent elevation and denudation of the Weald.

Although some of the Eocene outliers lie many miles from the two great basins, there are none beyond the outcrop of the Chalk, and there is accordingly no positive evidence that the Eocene sea spread westward of the present escarpment of the Chalk.

Throughout the south of England the Eocene consists of sands and clays, with pebble-beds and seams of lignite in some localities. Limestones are absent, and by far the greater part of the material is of terrigenous origin. The sea must have been shallow, and large rivers brought full loads of sediment from the neighbouring land. In the east the deposits are entirely marine, but towards the west some of the beds contain brackish-water shells and remains of plants, and were evidently laid down in the estuary of a great river flowing from a land area in the west.

But while normal sedimentation proceeded quietly in the south of England, the north-west of the British Isles was a scene of extraordinary volcanic activity. A series of basaltic volcanoes developed, and here and there great masses of plutonic rock were intruded. The lavas formed extensive plateaus, of which the remains may still be seen in Antrim, the Inner Hebrides and the west coast of the Scottish mainland. Intercalated between the basalt-flows are occasional lenticular patches of sedimentary deposits containing an Eocene flora.

The Eocene beds of the south of England rest upon the Chalk, and generally without any visible unconformity. Often, indeed, the surface upon which they lie is very uneven and greatly eroded. But much of this erosion took place after the Eocene beds were laid down.

At the base of the Eocene there is commonly a layer of unworn flints, similar in their irregular form to the flints of the Chalk below. Evidently they were never rolled by rivers nor exposed to atmospheric weathering. But the Chalk has been dissolved by percolating water beneath the Eocene covering, and the insoluble flints were left behind.

Although the irregular surface of the Chalk cannot be taken as evidence of unconformity, and although no discordance is visible in single sections, an examination of a larger area shows that there must have been a considerable amount of denudation before the Tertiary beds were deposited. In Hampshire and the Isle of Wight the Eocene rests upon the *mucronata* zone, in Hertfordshire upon the *Micraster* zones.

Even the *mucronata* zone is not the top of the Cretaceous system, and in England the highest zones if ever deposited were removed completely before the Tertiary beds were laid down.

Fauna and Flora.—In England the fauna of the Eocene is totally unlike the fauna of the Chalk, and the cause of the difference has already been discussed. Because the sea was muddy the fauna of the English Eocene consists for the most part of gastropods and lamelli-

branchs, but other groups are also represented. Foraminifera are much less important than in the Chalk. *Nummulites*, however, is a characteristic genus which occurs in crowds in some of our English deposits. In the Mediterranean region and its continuation in Asia it forms massive beds of limestone. Corals are generally rare. *Litharaea websteri*, from the Bracklesham series, is one of the few forms found in any abundance. Echinoderms, too, are seldom met with. *Schizaster* occurs in the Barton beds. Brachiopods have entirely lost their former importance. *Lingula, Terebratula*, and one or two other genera still survive, but they are not common. Gastropods and lamellibranchs, on the other hand, are very abundant. Amongst the gastropods the siphonostomatous forms predominate. *Fusus, Voluta, Conus, Pleurotoma*, are common in the marine beds; *Cerithium, Melania* and *Potamides* in the brackish-water deposits. The lamellibranchs include *Corbula, Cardita, Cardium, Chama*, etc., Cephalopods are by no means common. The ammonites and belemnites are entirely extinct; but nautiloid forms such as *Nautilus* and *Aturia* are still met with. Decapod crustaceans are often found. Among the macrurous forms are *Hoploparia* and *Meyeria*; amongst the brachyurous forms, *Xanthopsis* and *Dromia*.

Vertebrates occur in considerable abundance in some localities. Sharks' teeth, such as *Lamna* and *Otodus*, are common, and remains of teleostean fishes are also found. Tortoises, turtles and crocodiles are the principal reptiles. Several genera of birds are also known. But the most striking feature of the period is the sudden appearance of numerous placental mammalia. These include carnivores, ungulates and lemuroids. A considerable number of species have been found in England; and many more in France, America, and elsewhere.

Remains of plants are very abundant in some beds, and they appear to indicate considerable changes of climate during the period. The flora in general differs in degree rather than in general composition from that of the late Cretaceous. The Flowering Plants (Angiosperms) are now well established as the dominant group. The Reading Beds near the base of the system yield a warm temperate flora, including *Laurus* and *Platanus*, whilst the flora of the London Clay is definitely subtropical (see below) as is that of the Bracklesham Beds, but towards the close of the Eocene the climate began to cool down again judging by the flora.

The London Basin

In the London Basin the Oligocene is entirely absent, and even the upper part of the Eocene has been removed by denudation; but the Lower Eocene is better developed than in the Hampshire Basin.

The beds are grouped as follows:

Barton beds.
Bracklesham beds.
Bagshot beds.
London Clay.

Lower London Tertiaries $\begin{cases}\text{Blackheath and Oldhaven beds.}\\ \text{Woolwich and Reading beds.}\\ \text{Thanet Sands.}\end{cases}$

The Lower London Tertiaries form a narrow border around the basin, widening to the east of London into a fairly extensive but very irregular band. The London Clay fills the basin and covers by far the greater part of the area. Here and there, however, it is overlaid by the Bagshot and later beds, which form low hills or plateaus rising above the general level. Owing to their sandy character these elevated tracts are by nature heaths or commons. The largest lies to the north of Guildford and stretches about twenty-five miles from east to west, and about twelve miles from north to south. It includes Aldershot Common, Ascot, Bisley, Bagshot Heath, etc.

Nearer to London, Highgate Hill and Hampstead Heath are capped by the sands and gravels of the Bagshot series; many other outlying patches occur, especially at Harrow and in Essex.

The Lower London Tertiaries as a whole are thickest on the southern margin of the basin, especially in the east; and they thin towards the north.

The **Thanet Sands** are generally light-coloured sands, but towards the base they become argillaceous and full of glauconitic grains. Where they rest upon the Chalk there is usually a layer of unworn, green-coated flints. After the sands had been deposited, percolating water continued to dissolve the Chalk beneath, and the flints were left behind. The green coating is probably due to the glauconite in the sands.

The Thanet Sands are well developed in the Isle of Thanet, but they are overlapped towards the west and north. The fossils are entirely marine, and are chiefly lamellibranchs and gastropods—for example, *Corbula regulbiensis* and *Aporrhais sowerbyi*.

The **Woolwich and Reading Beds** are more variable. In the east of Kent the series consists throughout of light-coloured false-bedded sands containing marine fossils. In the western part of Kent and in East Surrey it is formed partly of sands, partly of grey clay, generally full of estuarine shells, sometimes with bands of oysters. Towards Reading it consists of mottled plastic clay and variegated sands, generally unfossiliferous, but sometimes with remains of plants. The Reading type occurs also along the northern margin of the basin, in Hertfordshire and Essex. Sometimes it includes a bed of flint pebbles cemented into a hard conglomerate known as the Hertfordshire Pudding-stone.

Amongst the marine fossils of this series are *Ostrea bellovacina*, *Cyprina morrisi*, etc.; amongst the fresh-water and estuarine forms

are *Unio, Cyrena, Viviparus.* Remains of fishes, reptiles, birds and mammals have also been found.

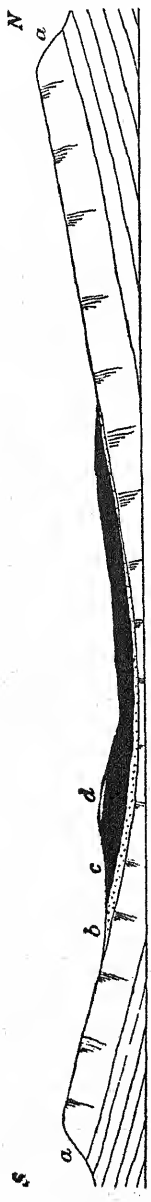


FIG. 124.—DIAGRAMMATIC SECTION ACROSS THE LONDON BASIN.
a, Chalk; *b*, Lower London Tertiaries; *c*, London Clay; *d*, Bagshot Beds.

In the neighbourhood of London the sands of the Woolwich series are overlaid by a considerable thickness of current-bedded gravels which have sometimes been distinguished as a special subdivision under the name of the **Blackheath Pebble-Beds.** They consist chiefly of well-rounded flint pebbles in a fine sandy matrix. The junction with the sands below is usually sharp and often very irregular, as if the surface of the sands had been eroded.

In the eastern part of Kent the place of these pebble-beds is taken by the **Oldhaven Beds,** which consist of fine drab-coloured sand, with a bed of flint pebbles at the base.

The **London Clay** occupies by far the greater part of the basin. It is usually a fine bluish-grey clay, which weathers brown towards the surface. It commonly contains pyrite and crystals of selenite, and also layers of septaria. The last are concretionary masses consisting of a mixture of clay and carbonate of lime. In some districts they are the only hard stones available, and accordingly have been used in many of the older buildings; and they have also been employed in the manufacture of cement. The London Clay is 400 or 500 feet thick near London, but towards the west it thins and is partly replaced by sands. Fossils are not generally common. Amongst the characteristic forms are *Ditrupa plana, Aporrhais sowerbyi, Aturia ziczac, Voluta wetherelli.* In the Isle of Sheppey and elsewhere the remains of plants, mostly pyritized, are found. Recent work has shown that the greater part of the genera represented, such as *Nipa, Magnolia, Cinnamomum, Sabal, Sequoia,* etc., live to-day in subtropical regions, the bulk of them in Indo-Malaya. Most of the remains are pyritized fruits and seeds, which careful examination has shown to have grown fairly close to the place of deposition.

The London Clay becomes sandy towards the top and passes up without a break into the Bagshot beds above.

As fossils are rare and the lithological change is gradual, no very definite line can be drawn between the two formations; and it is by no means improbable that the sands of one locality may be in part contemporaneous with the clay of another.

The **Bagshot Beds** consist chiefly of light-coloured sand with pebble-beds in some localities and subordinate beds of clay; and generally they are strongly current-bedded. Fossils are rare, but remains of plants are occasionally found, and casts of marine shells have been met with at the top of the formation near Woking.

The **Bracklesham and Barton Beds** are similar to those of the Hampshire basin (see p. 442), though less fossiliferous.

Scattered over the Chalk Downs of southern England in many places are large blocks of hard sandstone called Sarsen stones (or Greywethers, from their resemblance to sheep when seen at a distance). They may be as much as 10 or 15 feet long and 2 to 4 feet high. They are masses of sand from the Eocene beds which have been cemented by silica in a manner analogous to the surface quartzites of South Africa, and have resisted denudation when the rest of the beds were removed after the Miocene uplift.

The Hampshire Basin

The Hampshire Basin is a roughly triangular area stretching from near Dorchester on the west to Worthing on the east, and from the middle of the Isle of Wight on the south to the neighbourhood of Salisbury on the north. It is bounded on the south by a monoclinal flexure which runs through the Isles of Wight and Purbeck (see Fig. 125).

In the steep northern limb of this flexure the strata stand nearly vertical, and the outcrops of the Chalk and Eocene are consequently very narrow. The continuity of the basin is broken by several other parallel folds, one of the most important of which runs past Chichester and Portsdown.

In this area the Lower Eocene, including the London Clay and the Lower London Tertiaries, is somewhat thinner than in the London district; and it appears only upon the margin of the basin. The upper beds, on the other hand, are far more fully developed, and together with the succeeding Oligocene they fill the greater part of the basin.

The general succession is as follows:

Upper Eocene	Barton beds. Bracklesham beds.
Lower Eocene	Bagshot beds. London Clay. Reading beds.

The Thanet Sands are absent and the Lower London Tertiaries are represented by the **Reading Beds** alone. These are similar in

character to the Reading beds of the western extremity of the London Basin.

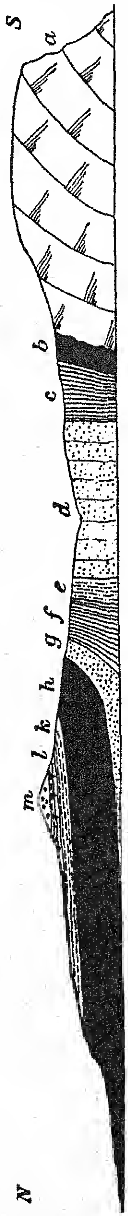


Fig. 125.—Section of the Isle of Wight, Totland Bay to Headon Hill. (After H. W. Bristow.)
a, Chalk.—Eocene: *b*, Reading Beds; *c*, London Clay; *d*, Lower Bagshot Beds; *e*, Bracklesham Beds; *f*, Barton Clay; *g*, Barton Sand.—Oligocene: *h*, Headon Beds; *k*, Osborne Beds; *l*, Bembridge and Hamstead Beds.—Recent: *m*, Gravels.

The **London Clay** is similar to that of the London Basin, but on the whole is more sandy, especially in Dorsetshire. In the Isle of Wight it appears to thin from east to west; but in the folding to which this area has been subjected it is not possible for the strata to preserve their original thicknesses throughout.

The **Bagshot Beds** consist chiefly of light-coloured sands with beds of clay. Fossils are generally rare, but in a seam of pipeclay at Alum Bay leaves and other remains of plants have been found in abundance. Like the plants of the London Clay, they indicate a warm if not a tropical climate.

Owing to the unfossiliferous nature of most of the deposits, the upper limit of the series cannot be determined with certainty. At the eastern end of the Isle of Wight a thickness of about 100 feet is sometimes assigned to the Bagshot, at the western end about 660 feet. But it is probable that a considerable part of the latter may belong to the succeeding Bracklesham series.

The **Bracklesham Beds** are in part of estuarine origin and in part marine. Like the Bagshot, they consist of sands and clays. But at the eastern end of the basin the argillaceous material predominates, and the difference between the two series is fairly marked. At the western end of the basin both the Bracklesham and Bagshot beds consist chiefly of sands, and no very definite line can be drawn between the two formations. The change in the character of the deposits is accompanied by a change in the fossil contents. In the east the Bracklesham beds contain an abundant fauna of Mollusca and Foraminifera; in the west remains of plants predominate, and marine fossils are limited to a small part of the series. It is evident that the eastern end of the Hampshire Basin

lay beneath the sea, while the western end was occupied by an estuary.

The Bracklesham beds form the foreshore on both sides of Selsey Bill; they are well exposed in the cliffs of Whitecliff Bay and Alum Bay, at the eastern and western ends of the Isle of Wight; and they are also shown on the Hampshire coast near Bournemouth. At Selsey Bill they have yielded a large series of marine fossils, and palm-fruits (*Nipa*) are found in the lower beds. But it is at Whitecliff Bay that the succession can be most conveniently studied. Here the deposits are yellow and green sands, sandy clays, and green and blue clays. *Nummulites variolaris* is characteristic of the upper part of the series, *Nummulites laevigatus* of the lower part. Other Foraminifera also occur, and also many marine Mollusca such as *Venericardia planicosta*, *Turritella imbricataria*. At Alum Bay the lower part of the series consists of light-coloured sands, with beds of clay and seams of lignite, and contains no recognisable fossils. It is impossible, therefore, to define the lower limit of the series. But above these unfossiliferous deposits lie dark sandy clays with a marine fauna similar to that of Whitecliff Bay and Selsey Bill, but far less rich in species. Near Bournemouth the greater part of the Bracklesham series consists of sands. The characteristic Bracklesham shells appear in some of the beds, but the principal fossils are plants, many of which are beautifully preserved in the pipe-clay beds. They include genera such as *Gleichenia*, *Smilax*, *Acacia*, *Lygodium*, *Diospyros* and some of the London Clay types, an assemblage of distinctly sub-tropical affinities.

The **Barton Beds** are well exposed at Barton on the coast of Hampshire, and also in the Isle of Wight. The lower part, which is often called the Barton Clay, consists chiefly of sandy clays, and clays with septaria. Fossils are extraordinarily abundant. *Nummulites elegans* is found near the base. The mollusca include *Crassatella sulcata*, *Fusus* (*Clavella*) *longaevus*, *Xenophora agglutinans*, *Rimella rimosa*, *Voluta luctatrix*, and *Typhis pungens*.

Above the Barton Clay is a mass of yellow and white sands, known as the Barton Sands, or Upper Barton, or sometimes as the Headon Hill Sands. At the base the sands become argillaceous and contain *Chama squamosa* and other fossils. Another clayey bed occurs higher up in the series at Barton. In the Isle of Wight the sands above the *Chama* bed are generally unfossiliferous; but at Barton brackish-water shells, such as *Cerithium pleurotomoides*, occur towards the top.

During Eocene times there was great igneous activity in a strip of country extending from North-east Ireland to the Isle of Skye; in the Faroe Islands; Iceland; and Jan Mayen Island. Till lately it has been believed that this was a continuous area of fissure eruptions forming a gigantic basalt plateau. But there are many difficulties in

this explanation, which cannot be discussed here in detail. It seems now to be established that each of the great masses of basalt lavas in Antrim, Mull, Ardnamurchan and Skye represents the wreck of a great shield-volcano, or pile of shield-volcanoes, like Hawaii. Major centres of eruption have been localised in Arran, Mull, Ardnamurchan and Skye, though not in Antrim. At a later stage in each of these areas plutonic intrusion on a large scale took place at or about the same centres, as is set forth in Chapters XII and XXVIII. For details of the highest interest reference should be made to petrological textbooks or to the Memoirs of the Geological Survey; especially to *British Regional Geology: Scotland, The Tertiary Volcanic Districts*, 1935. Dyke-swarms radiating from some of these centres extend over southern Scotland, and one, the Cleveland Dyke, almost reaches the coast of Yorkshire. Fossil plants in sediments interbedded here and there with the basalt flows indicate an Eocene age for the eruptions.

THE OLIGOCENE

The Oligocene system plays a very subordinate part in British geology; and if our area were alone concerned, there would be little justification for separating it from the Eocene. Formerly, indeed, the two systems were united. In Germany, however, the Oligocene is a far more important formation. At the close of the Eocene period there were very considerable changes in the geography of Western Europe. South-eastern England, which was then sea, became land, and Northern Germany, which was then land, became sea. It is chiefly on account of these changes that it has been found convenient to divide the Oligocene from the Eocene. In England the Oligocene is found only in the Hampshire Basin and possibly in Devonshire.

Hampshire Basin.—The Oligocene covers the northern part of the Isle of Wight and a considerable area on the other side of the Solent. It rests quite conformably upon the Eocene, but was formed under different conditions. The Eocene as a whole is a marine formation with occasional estuarine intercalations. The Oligocene, on the other hand, consists of fresh and brackish-water deposits, with only one or two marine beds. There is, however, no sharp line between the two systems, and the Headon Beds are placed by some in the Eocene.

So far as the lithological nature of the deposits is concerned, there is but one important difference between the two formations. Sands and clays form the greater part of both, but in the Oligocene there are several beds of limestone. They are not limestones of the usual type, for they are full of fresh-water shells. Similar calcareous deposits have been formed in recent times in some of the meres of the Fen District.

The marine and brackish-water fossils in the Oligocene do not differ

in any marked respect from those of the Eocene. The fauna is naturally not so rich, but it is of the same type. Gastropods and lamellibranchs still predominate, and the genera are all survivors from the Eocene sea. The fresh-water fauna also consists chiefly of Mollusca, especially gastropods. Most of the genera found in our present ponds and rivers are represented. The common forms are the gastropods *Limnaea*, *Planorbis*, and *Viviparus*, and the lamellibranchs *Unio* and *Cyrena*. Land snails, such as *Helix* and *Amphidromus*, also occur.

Mammalian remains have been found in considerable abundance. *Hyopotamus*, *Anoplotherium*, *Palaeotherium* and *Chaeropotamus* are the commonest forms.

Remains of plants occur in some of the beds. The nucules of *Chara*, a fresh-water alga, although small, are conspicuous in the Bembridge Limestone.

The Oligocene of the Hampshire Basin is divided as follows:

Hamstead Beds. Chiefly fresh-water; brackish-water and marine towards the top.
Bembridge Marls. Fresh-water; marine bed near base.
Bembridge Limestone. Fresh-water.
Osborne Beds. Fresh and brackish-water.
Headon Beds. Fresh-water, brackish-water and marine.

But with the exception of the Bembridge Limestone, none of these divisions are very clearly defined, either lithologically or palaeontologically. The whole succession appears to represent only a part of the continental Oligocene.

The Headon series consists of clays, marls, and sands, with occasional beds of limestone and seams of lignite. It is commonly divided into Lower, Middle and Upper Headon. The Lower and Upper Headon beds are of fresh-water and brackish-water origin; but the Middle Headon is to a large extent marine. *Cytherea incrassata* is the characteristic fossil of the marine beds. *Ostrea velata* sometimes forms thick banks, and many other marine shells occur. The principal fresh-water forms are *Planorbis euomphalus*, *Limnaea longiscata*, and amongst the lamellibranchs *Erodona* and *Cyrena*.

The Osborne Beds near the axial line of the Isle of Wight are red and green clays with some fresh-water limestones. But in the north of the island they consist of hard grits and limestones with sands and marls above. One of the beds of clay is crowded with the remains of a small fish, *Clupea vectensis*. The principal fossils are fresh-water shells such as *Limnaea longiscata* and *Planorbis obtusus*, and brackish-water forms such as *Melania excavata*.

The Bembridge Limestone consists of hard beds of white or cream-coloured stone, separated by layers of clay or softer limestone. It is entirely a fresh-water deposit. *Planorbis discus* and *Viviparus orbicularis* are common; various species of the land-shells *Amphidromus*

and *Helix* occur; and the nucules of *Chara* are abundant. Mammalian remains are also found.

The Bembridge marls are mostly of fresh-water origin, but at Whitecliff Bay a marine bed with *Cytherea incrassata* and *Ostrea vectensis* occurs near the base.

The Hamstead beds are also marls. The lower and larger part consists of red, green and dark-coloured clays, with *Unio*, *Viviparus*, and remains of reptiles, mammals and plants. These are entirely of fresh-water or estuarine origin. The upper part, about thirty feet in thickness, is also composed mostly of clay; but it contains marine and brackish-water shells, such as *Corbula vectensis*, *Ostrea calligera*, *Potamides plicatus*, etc.

Devonshire.—Between Newton Abbot and Bovey Tracey, on the Teign, is a broad low-lying tract of heath almost completely shut in by higher ground. This basin-shaped depression, which measures about nine miles by four, is occupied by gravels, sands and china-clay, which rest directly and unconformably upon the Devonian and Carboniferous rocks. Lignite occurs at the Bovey end of the basin in sufficient quantity to be worked for fuel. Plant-remains are abundant in some places, and amongst them are *Osmunda*, *Sequoia*, etc. These beds were formerly referred to the Bracklesham series, but it now seems more probable that they are of early Miocene age.

CHAPTER XXV

THE MIOCENE AND PLIOCENE SERIES

THE MIOCENE

No marine Miocene deposits are known in the British Isles, and during the Miocene period not only our own country but also the greater part of Northern Europe was land. The North Sea, however, was already in existence, for marine beds of this age are present in Schleswig-Holstein, the north-west of Germany and the Netherlands area. The Atlantic spread into the basins of the Loire and the Garonne. From the Mediterranean an arm proceeded around the outer border of the Alps and the Carpathians into the south of Russia, and through the Vienna gap into the plain of Hungary.

In the south of Europe it was a period of gigantic changes. A great part of the Alpine folding took place in Miocene times. Arms of the sea were cut off and for a time became salt lakes. It was in one of these that the famous salt deposits of Wieliczka were formed. Towards the end of the period the salt lakes were gradually converted into fresh-water lagoons.

Of the great earth-movements that produced these changes some indications may be seen in the south of England. The sharp monoclinal fold of the Isle of Wight belongs to this period, for it affects the Oligocene beds; and no doubt the other similar and parallel folds, and the anticline of the Weald, were formed about the same time. At least they are post-Eocene in date. These folds were accompanied by a considerable amount of over-thrusting, which is well displayed in the cliffs of the Dorset coast.

THE PLIOCENE

The Pliocene (Fig. 123, p. 435) differs from the preceding systems chiefly in its fauna. The greater number of the invertebrates belong to living species; but of the vertebrates the species are mostly extinct, though many of the genera still survive. Where deposition has been continuous no sharp line can be drawn between the Miocene and Pliocene; but in England, owing to the absence of the Miocene, the base of the Pliocene is perfectly defined and is marked by an unconformity. The upper limit, however, is indeterminate and artificial.

In England the Pliocene consists largely of shelly sands and gravels, known locally as Crag. Often the fragments of shell form the bulk

of the material. False-bedding is common, and the deposits were evidently laid down in shallow seas where tides and currents had full play. There are, however, beds of laminated clay which appear to be of estuarine origin.

The largest area of Pliocene in England lies along the East Anglian coast, extending with but little interruption from the mouth of the Stour to Weybourn, west of Cromer. Between the Stour and Walton-on-the-Naze there are a few small outliers.

Pliocene deposits also occur in patches on the Downs of East Kent, at a height of about 600 feet above the sea, thus proving that there has been a considerable amount of earth-movement since the period commenced. There are some small patches along the line of the North Downs from Guildford to a point north of Sevenoaks, and one or two near Berkhamsted and Rothamsted in Herts, and, on the other side of England, a small patch of Pliocene has been found at St. Erth, south of the Bay of St. Ives, in Cornwall. In Ireland some shelly sands and gravels beneath the boulder-clay of Wexford have been referred to the Pliocene period.

Fauna.—The fauna of the English Pliocene is very rich both in species and in individuals. Lamellibranchs and gastropods form by far the largest part. All the genera persist to the present day, and they are all inhabitants of shallow seas. Many of the species, however, are extinct; and of those which still survive, some are now found only in warmer seas, some in the northern oceans, while others continue to dwell upon our own shores. The southern forms predominate in the lower part of the Pliocene, the northern forms in the upper part. Next to the Mollusca, the Foraminifera and Polyzoa are the most important groups. Some of the latter were formerly known as corallines, and hence the name of Coralline Crag applied to a part of the system. *Theonoa* (*Fascicularia*) and *Alveolaria* are common forms. Corals are not unknown, but they are relatively rare. Echinoids are sometimes abundant. Amongst the genera found are *Echinocyamus* and *Temnechinus*.

Vertebrate remains are common in the nodule bed at the base of the East Anglian Crags. But they are mostly derivative, and have been washed out from some older deposit. Sharks' teeth and bones of cetaceans are especially abundant; and remains of *Mastodon*, *Rhinoceros*, *Elephas* and other land mammalia are common. Terrestrial mammalia are also abundant in the Cromer Forest bed at the top of the Pliocene, and remains of birds, reptiles and amphibians have been found.

Classification.—Many minor subdivisions have been recognised in the Pliocene deposits; but it is comparatively seldom that they are found in superposition. The determination of their relative age is therefore often based upon purely palaeontological evidence. In

general, the older the deposit the smaller is the proportion of living forms that it contains. But it is obvious that this criterion cannot be applied except in the case of deposits which were formed under similar conditions. Evolution does not everywhere proceed with the same rapidity. In the deep seas, for example, it seems to be a slower process than in shallow water. Moreover, the rate of change is not the same throughout the animal kingdom. Thus, it has already been remarked that most of the Pliocene vertebrates are now extinct, while a large proportion of the invertebrates survive. Any comparison must therefore be restricted to a particular group or class of animals or plants. It is usual to take the percentage of living and extinct Mollusca as a standard.

Eastern England

In the east of England the following subdivisions are usually recognised:

7. Cromer Forest-bed Series.
6. Weybourn Crag.
5. Chillesford beds.
4. Norwich Crag.
3. Red Crag.
2. Coralline Crag.
1. Lenham beds.

The Lenham Beds form a number of small patches on the top of the North Downs, between Maidstone and Folkestone, at a height varying from about 500 to 620 feet above the sea. In several cases they owe their preservation to the fact that they have fallen into pipes formed by the solution of the Chalk beneath. They are mostly glauconitic sands. Owing to oxidation of the glauconite the sands often become brown, or are even compacted into a kind of hard ironstone. The Lenham beds appear to be the oldest of our Pliocene deposits. The fauna consists chiefly of shells, and is not unlike that of the Coralline Crag. It includes, however, a few species unknown in that formation, but found in the Miocene. Amongst these are *Pleurotoma jouanneti*, *Terebra acuminata* and *Arca diluvii*.

Sands of similar petrographical constitution occur upon the Downs in Surrey, but they have not yet yielded recognisable fossils.

The **Coralline Crag** is known only in the south-east of Suffolk. The principal outcrop is in the neighbourhood of Aldeburgh and Orford, but small patches occur further south at Sutton, Ramsholt and Tattingstone (cp. Fig. 126). At its base at Sutton there is a phosphatic nodule bed containing fossils derived from the London Clay below, but including also vertebrate remains, some of which may belong to the Pliocene period. There are also blocks of sandstone known as box-stones, which seem to have been derived from some deposit of about the same age as the Lenham beds.

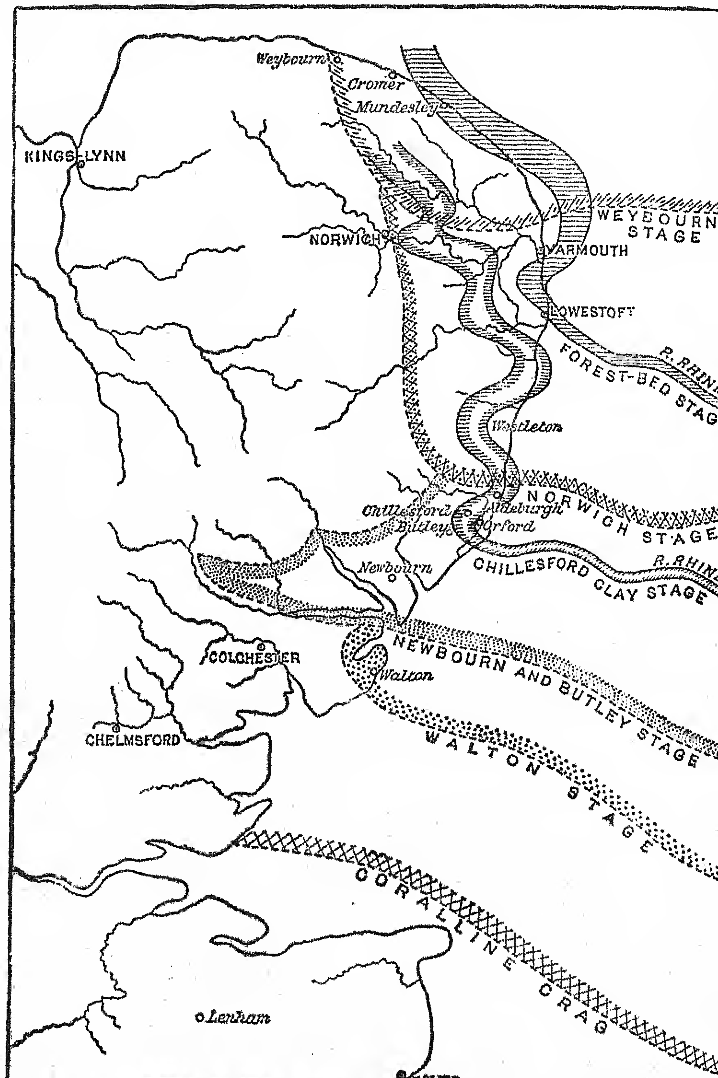


Fig. 126.—Attempted Restoration of the Distribution of Land and Water during Successive Stages of the Pliocene Epoch. (By Mr. F. W. Harmer.)

The rest of the Coralline Crag is made of light-coloured sands and beds of comminuted shells and Polyzoa. The upper part is sometimes cemented into a soft limestone, and is darker in colour.

Amongst the common fossils are the large brachiopod *Terebratula grandis* and several species of echinoids. But far more important are the Mollusca and Polyzoa, both of which occur in such profusion as to form a large proportion of the deposit. *Theonoa aurantium* and *Alveolaria semiovata* are two of the common polyzoans. Of the Mollusca some 30 or 40 per cent. are extinct. *Astarte omalii* and *Voluta lamberti* may be cited as examples. Of the species which still survive, about 20 per cent. no longer live so far north, but are found in the Mediterranean, as, for example, *Cardita corbis*, *Limopsis pygmaea* and *Ringicula buccinea.* It is evident, therefore, that during the deposition of the Coralline Crag the British seas were warmer than at present.

At the present day the **Red Crag** is practically confined to a triangular area about the mouths of the Stour and Orwell, with Walton-on-the-Naze, Sudbury and Aldeburgh at the three corners. But it may have had a greater extension, and doubtful traces have been found as far away as Thaxted in the north-west of Essex. It is usually a red or brown shelly sand deeply stained by oxide of iron. Generally it is darker than the Coralline Crag, but the colour of both is variable. On the whole, too, it is more quartzose and less calcareous, but nevertheless some of the beds are made up largely of fragments of shells. There is often a nodule bed at its base.

Before the Red Crag was deposited the Coralline Crag had been almost entirely worn away. Here and there, however, it was left as reefs or shallows in the Red Crag sea. Accordingly the Red Crag generally rests upon an eroded surface either of the London Clay or of the Coralline Crag, and at Sutton it is banked against the latter as a beach is banked against a cliff.

The fauna of the Red Crag is rather more modern than that of the Coralline Crag. But there are considerable variations in the Red Crag itself. At the Naze it contains a smaller percentage of living species than at Newbourn, and at Newbourn a smaller percentage than at Butley. That is to say, the proportion of living forms increases from south to north. The sea-coast lay towards the south, and gradually the deposits spread northwards from the shore; and thus the southern part of the Red Crag is older than the northern.

Not only is the fauna newer than the fauna of the Coralline Crag, but it is also of a more northern type. The Coralline Crag contains a number of species which no longer live in the North Sea, but are found in the Mediterranean. The Red Crag also includes forms which do not now inhabit the neighbouring waters. Some of them still dwell in more southern seas, but others are now found only in the boreal

ocean. From Walton to Butley the proportion of southern forms diminishes and the proportion of northern forms increases.

The fauna of the Red Crag is very rich both in species and individuals. Polyzoa, however, are rare except in the Walton deposit, which in other respects also shows affinities to the Coralline Crag. Gastropods and lamellibranchs predominate. *Venus casina*, *Pectunculus glycimeris* and *Neptunia contraria* are common forms of which the first two still live in British waters and occur also in the Coralline Crag. *Admete viridula*, *Cardium groenlandicum* and *Nuculana lanceolata* are species now known only in more northern seas. The small echinoid *Echinocyamus pusillus* occurs in profusion at Walton and elsewhere.

The **Norwich Crag** begins at Aldeburgh where the Red Crag ends, and extends along the Suffolk and Norfolk coasts as far as the river Bure. It thickens rapidly from south to north, and also from west to east, and is about 150 feet in thickness at Southwold. It consists of sands and clays and pebbly gravels, but never exhibits the beach-like bedding characteristic of the Red and Coralline Crags. Moreover, it is less uniformly fossiliferous. In many of the sections no organic remains have been found; but in others impersistent shelly beds occur, which have yielded an abundant fauna. On the whole, it appears to be a delta deposit rather than a beach or sand-bank. At the base is a bed of flints and pebbles in which mammalian remains have been found, as in the nodule bed at the bottom of the Red and Coralline Crags.

A considerable interval of time appears to have elapsed between the deposition of the Norwich and the Red Crags, for the two faunas are decidedly distinct. In the Norwich Crag the proportion of extinct forms is less, and that of northern forms considerably greater. The change that began in the Red Crag period was continued and the climate was growing colder.

The fauna of the Norwich Crag is less rich than that of the preceding stage. Of the common species of Mollusca nearly two-thirds live in the North Sea at the present day. Others, such as *Nucula cobboldiae* and *Tellina obliqua*, are extinct; and others are now found only in Arctic waters. *Astarte borealis* is the most important of the Arctic forms. It is abundant at Norwich, but becomes less common towards the south, and is unknown in the southern part of Suffolk.

The deposit which appears to be the next in order is the **Chillesford Clay** (Fig. 127). In the Bure Valley it rests upon the Norwich Crag; in the south of Suffolk upon the Red or the Coralline Crag. It is in general finely laminated, consisting of alternations of clay and sand, both of which are very micaceous. The fauna is marine.

The Chillesford Clay extends from Chillesford to Burgh in the valley of the Bure; but from west to east its extent is very limited. The exposures referred to it are confined within a narrow and meandering belt of country which widens from south to north. It has been sug-

gested that this belt represents an estuary of the Rhine, and that the open sea had retreated to the north.

In the north of Norfolk is another shelly deposit known as the **Weybourn Crag.** It is found on the coast west of Cromer, and has been recognised in the valley of the Bure, but south of Norwich it is

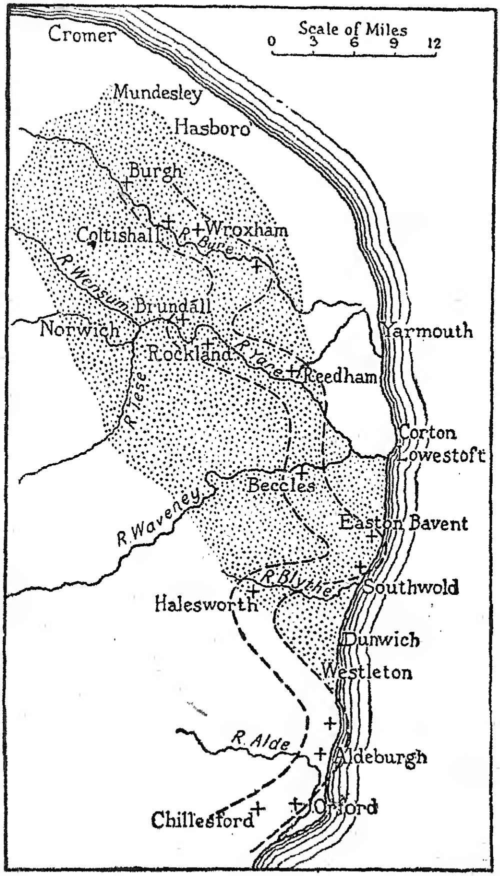


FIG. 127.—MAP SHOWING THE PRINCIPAL EXPOSURES OF THE CHILLESFORD CLAY (+) AND THE PROBABLE COURSE OF ONE OF THE ESTUARIES OF THE RHINE DURING THE CHILLESFORD AGE. (After Mr. F. W. Harmer.)

unknown. Its thickness is small, and its special feature is the great abundance of *Tellina balthica*, a shell which is quite unknown in the older beds.

Following the Weybourn Crag is a remarkable series of deposits displayed in the cliffs at Cromer and known as the **Cromer Forest-bed Series.** Here five beds have usually been recognised as Pliocene, but

as one of the two uppermost was undoubtedly formed under Arctic conditions, and the relative order of these two is by no means certain, it seems better to refer both to the Pleistocene, and to regard the Cromer Series as consisting of only three members, thus:

3. Upper Fresh-water Bed.
2. Forest Bed.
1. Lower Fresh-water Bed.

The middle member undoubtedly indicates a temperate climate: it consists of irregular layers of clay, sand and gravel, with stumps and stems of trees. The roots of the stumps are frayed and worn, and it is apparent that the trees are not where they originally grew, but have been washed into their present positions. Both the trees and the other remains of plants associated with them belong for the most part to species that live in East Anglia at the present day. The Forest bed also contains mammalian remains, such as *Elephas*, and a mixture of marine and fresh-water shells, including *Tellina balthica*. The fresh-water beds above and below contain plant-remains, land and fresh-water molluscs and small vertebrates. The lower fresh-water bed is seldom preserved.

West of England

The only deposits in the west of England which can with certainty be referred to the Pliocene period are those of St. Erth, in Cornwall. They lie at a height of about 100 feet above the sea, in the depression between St. Ives Bay and Mounts Bay. The area occupied is not more than a few acres in extent. The St. Erth beds are composed of loam, sand, and clay, with a little coarser material. A thin clay band near the top of the series has yielded about 90 species or marked varieties of Mollusca and 120 Foraminifera. Southern species of Mollusca occur, but no northern forms. Most of the Mollusca are found also in the older part of the Red Crag, and it is with this horizon, or with the Coralline Crag, that the St. Erth beds are provisionally correlated.

Ireland

Beneath the boulder-clay of Wexford, deposits of sand and gravel have been found with a rich molluscan fauna. Some of the beds, as in the East Anglian Crags, are made up largely of comminuted shells. Most of the species still live on the Irish shores, but a few are extinct and some are Mediterranean forms. The fauna is apparently Pliocene, and is believed to be somewhat more recent than that of St. Erth.

CHAPTER XXVI

THE PLEISTOCENE SERIES

From the foregoing chapters it is clear that during the greater part of the Tertiary the climate of southern England became progressively colder, as shown by the change from the palms of the London Clay to the Arctic shells of the latest Pliocene. This process, whatever the cause may have been, culminated in a period of intense cold in Northern Europe and America, when ice certainly covered vast areas of land. But as to the details of the history there exists a strange want of unanimity among geologists. It is a curious fact that there is more controversy as to what actually happened during the latest stages of geological history than in any earlier period. This is possibly because the evidence is too abundant and detailed, and does not admit of the broad and sweeping generalisations that have been applied to earlier periods. It may be well to say at once that no satisfactory explanation of the cause of ice-ages has yet been found, although it is universally admitted that such have occurred several times in different parts of the earth, even as far back as the Precambrian.

The Pleistocene period is generally divided into Glacial and post-Glacial stages, but these divisions have no chronological value, as it is evident that glaciation came to an end at different times in different places: in Britain it has definitely ended; in Norway there are still a number of glaciers; while Greenland is almost completely buried in ice. In much the same way subdivisions based on stages of human culture, Stone Age, Bronze Age, and Iron Age and so on, were not contemporaneous everywhere. We are as yet not in a position to fix in years the date of most of the Pleistocene deposits, though this has been done in a few instances, as in the case of the varve clays of Sweden. Hence it is necessary to remember that time-divisions can only be taken as relative, and as applying to limited areas. There is no positive proof that the great glaciation of North America happened at the same time as that of Europe, although it probably did. Hence each region can only be treated on its own merits.

In Britain one thing is certain, that there existed during the Ice Age a number of large animals, such as species of elephant and rhinoceros, that are now extinct, whereas all, or very nearly all the invertebrates still survive, though not all in and around the British Isles.

It is not necessary to discuss the fundamental point of the actual occurrence of an Ice Age in Northern Europe. This may now be taken

for granted, as also the fact of the existence of land ice (ice-sheets) on a vast scale, as opposed to the theory of submergence and floating ice. The main bone of contention among geologists is as to whether the glaciation of Britain consisted of one major advance and retreat of an ice-sheet with only slight fluctuations, or whether there were what may be described as definite interglacial periods, when the ice disappeared altogether, and the climate may even have been somewhat milder than at present. Without going into detail it may be said that the balance of opinion now inclines to the view of what may be called pronounced fluctuations, to use a somewhat non-committal term. In point of fact it is impossible to define an interglacial period, since it is known that the modern ice-fronts fluctuate everywhere and it is all a matter of degree. Until quite lately many of the large glaciers of the Alps were in the habit of advancing and retreating hundreds of yards at intervals of about 35 years, so that it could be said that any patch of land in their course was subject to glacial and interglacial periods of that length, thus reducing the whole thing to an absurdity. There is little evidence in Britain that there ever were intervals with a warmer climate than the present between the earliest advance of the ice and its final disappearance, though there almost certainly were *local* ice-free periods; it is, however, hardly possible to determine the extent of the areas then uncovered. It is well to remember that the highest mountains of Scotland are even now only a very few hundred feet below the theoretical line of perpetual snow for their latitude, and it is believed that a certain corrie on Ben Nevis has never been free from snow within the memory of man. Hence it may be taken as certain that there were glaciers in the Highlands all through the Ice Age, whatever may have been the state of affairs in the Lowlands.

One important modern development of the subject is the discovery that some of the divisions of the Stone Age of human culture can be correlated with various stages of the Glacial or more probably Interglacial deposits. The whole subject has become extremely complicated and hardly comes within the scope of this book, as it really forms part of a separate science; that of Prehistoric Archaeology. It will be discussed very briefly in a later section.

Some geologists separate from the Pleistocene the newest deposits of all, as Recent, but the distinction seems unnecessary, as well as impossible to define satisfactorily. The recent deposits are usually taken to be those containing only remains of animals still existing in this country, but it may be pointed out that animals are still becoming extinct in Britain, such as the wolf only two or three hundred years ago, and among birds, the Great Auk and the Bustard still more recently, while other forms are still preserved more or less artificially, and the same is true in many other parts of the world, even of races of man.

It is now commonly accepted by European geologists that there were in the Alps four main stages of maximum extension of the ice with intervening periods of much milder climate. This scheme has been to a considerable extent applied also to Northern Europe, and most British geologists now believe that there were very considerable fluctuations in the British Isles. In the present state of the question it is impossible to say anything dogmatic on the subject. The account here given of the deposits will be purely descriptive without theoretical extrapolation.

The Glacial Deposits

In England glacial deposits with boulders of northern origin extend southwards to a line joining the Bristol Channel and the mouth of the Thames. On the Continent the line is continued with a general easterly direction through Holland and Germany to the middle of Russia, where it bends towards the north. South of this line the northern boulders cease and no glacial deposits are found excepting in the immediate neighbourhood of mountain-chains.

The character of the deposits varies so greatly from place to place that nothing like a full description can be attempted, and only a short account can be given of a few typical districts.

Since it is only in East Anglia, as shown in the preceding chapter, that there is anything like a continuous series of deposits from the Pliocene to the Pleistocene, it is most logical to begin with that region.

Until recently it was the custom to include in the Pliocene the *Leda myalis* Bed and the Arctic Plant Bed that lie above the Cromer Forest series (p. 453). Now, however, it appears to be not quite certain which is the older of these, owing to possible glacial disturbance, and both are now generally assigned to the Pleistocene.

The *Leda* (*Yoldia*) *myalis* bed is a false-bedded loamy sand about 10 or 15 feet thick, with marine fossils. The chief species are *Yoldia myalis*, *Astarte borealis* and *Tellina balthica*, all very distinctly northern forms. The Arctic Plant Bed, which is impersistent, and not more than 4 feet thick, consists of peaty loam, with fragments of Arctic willow and Arctic birch and some fresh-water shells. It is seldom exposed, owing to changes in the cliffs and beach due to landslips and storms: it gives clear evidence of very cold conditions preceding the actual arrival of the ice.

The definitely glacial deposits of Norfolk have been subdivided into numerous stages each with a local name. The main feature is that they give clear evidence of four periods of advance of the ice, with intervening warmer intervals. Whether these last merit the name of interglacial periods may be left an open question, and it must not be assumed that the four periods of advance correspond with the four main glaciations of the Alps. It is in fact doubtful whether any deposits

equivalent to the earliest Alpine glaciation have been identified anywhere in Britain.

For glacial deposits of all kinds, including those formed during the warmer intervening stages, the term *Drift* is conveniently used. It is a relic of the days when all such deposits were attributed to gigantic floods, and is represented on the continent by the antiquated word *Diluvium*, derived from Noah's flood.

Using this nomenclature the glacial deposits of Norfolk can be divided into four main stages:

4. Hunstanton Boulder Clay.
3. Little Eastern Drift.
2. Great Eastern Drift.
1. North Sea Drift.

The material of the lowest division was deposited by an ice-sheet which came in from the North Sea: it consists mainly of boulder-clay containing abundant erratics partly derived from the bed of the North Sea and partly from Scotland and Scandinavia. Among these many rocks from the Oslo region, such as laurvikite and rhomb-porphyry, have been found. In some places there is a bed of sand up to 45 feet thick in the middle and above this far-travelled erratics are less common. This ice-sheet must have melted while floating, as the underlying beds are not ploughed up. Either the lower part or the whole of this series is often called the Cromer Till.

After a period of considerable river-erosion another ice-sheet, the Great Eastern Glacier, advanced from west of north, and overrode the earlier deposits, disturbing them a good deal and thus giving rise to what is commonly known as the Contorted Drift. The products of the glacier itself constitute the Chalky Boulder Clay, which is full of locally derived material, but has few far-travelled erratics, which are probably derived from the earlier drift. The Chalky Boulder Clay covers a very large area in the eastern counties. Immediately above it comes in places a series of sands and gravels, which seems to be material deposited during the melting back of the ice-sheet.

The third or Little Eastern ice-sheet was on a much smaller scale. It was responsible, among other things, for the well known Cromer gravel ridge or moraine and for certain sandy brickearths and coarse cannon-shot gravels in north Norfolk. These deposits contain much pale grey flint derived from Lincolnshire.

The fourth glaciation gave rise to a brown boulder-clay with erratics derived from northern England and Scotland, especially the Cheviot region. This is only found around Hunstanton and a few other places on the north coast of Norfolk.

It is thus clear that in East Anglia there were at least four periods of advance of ice-sheets from different directions, separated by periods of considerable local denudation. It may be mentioned that in recent

work on this subject the study of heavy minerals has proved of great service in separation and correlation of the different deposits, as the mineral assemblages derived from different sources, especially from Scandinavia, are very distinctive.

In southern Norfolk and Suffolk the earliest glacial deposit is the Westleton Shingle, which represents marine shore-deposits in front of an advancing ice-sheet. This is followed by the Norwich Brick-earth, a decalcified boulder clay, equivalent to the Cromer Till, and above this are various sands and gravels, formerly called the Mid-Glacial Sands and Gravels. The boulder clay of the second glaciation contains in addition to Chalk a large amount of Jurassic material since it came from further west in the Midlands than that in north Norfolk, but there are still a good many Scottish boulders. The rest of the succession is not very clear and the fourth glaciation is probably not represented at all. Some of the Cannon-shot Gravels found on high ground in Norfolk and Suffolk are probably due to the Little Eastern ice-sheet.

In the Cambridge region the glacial deposits have undergone a great deal of erosion and only remain on the higher ground. It is clear, however, that the earliest deposit still existing is the Chalky Boulder Clay, which covers a very large area, extending approximately as far west as the Great Ouse–Thames watershed near Buckingham. The rest of the succession is very complicated and there is still much difference of opinion on the subject. The theory that some of the gravel deposits were the products of an Ancient River System transverse to the modern drainage has now been abandoned. Much of the glacial material appears to have been laid down as outwash fans in front of the retreating ice, and much importance is now attributed to the formation of the so-called 'Taele' deposits, which probably are portions of such torrential fan deposits formed when the ground was partly frozen. In this area there were at least two periods of ice-extension and possibly more. It is evident that in the earlier stages the land stood much higher than now, as some drift-filled preglacial valleys descend far below sea level.

In the Midlands generally there is also evidence of a complicated glacial history not so well known as that of East Anglia. There are relics of an ancient high-level drift, deeply denuded and cut into by many valleys, with erratics derived from several distant sources. This may be equivalent to the North Sea Drift of Norfolk and the high level boulder clays of East Yorkshire. This is succeeded by a drift derived from the north-east, north or north-west, due to the confluence of ice from several directions and probably equivalent to the Great Eastern Ice Sheet of Norfolk. Even in this there is evidence of at least two stages of advance and retreat.

In East Yorkshire the two earlier glaciations of Norfolk are probably represented by the high-level drifts of the Cleveland Hills and the

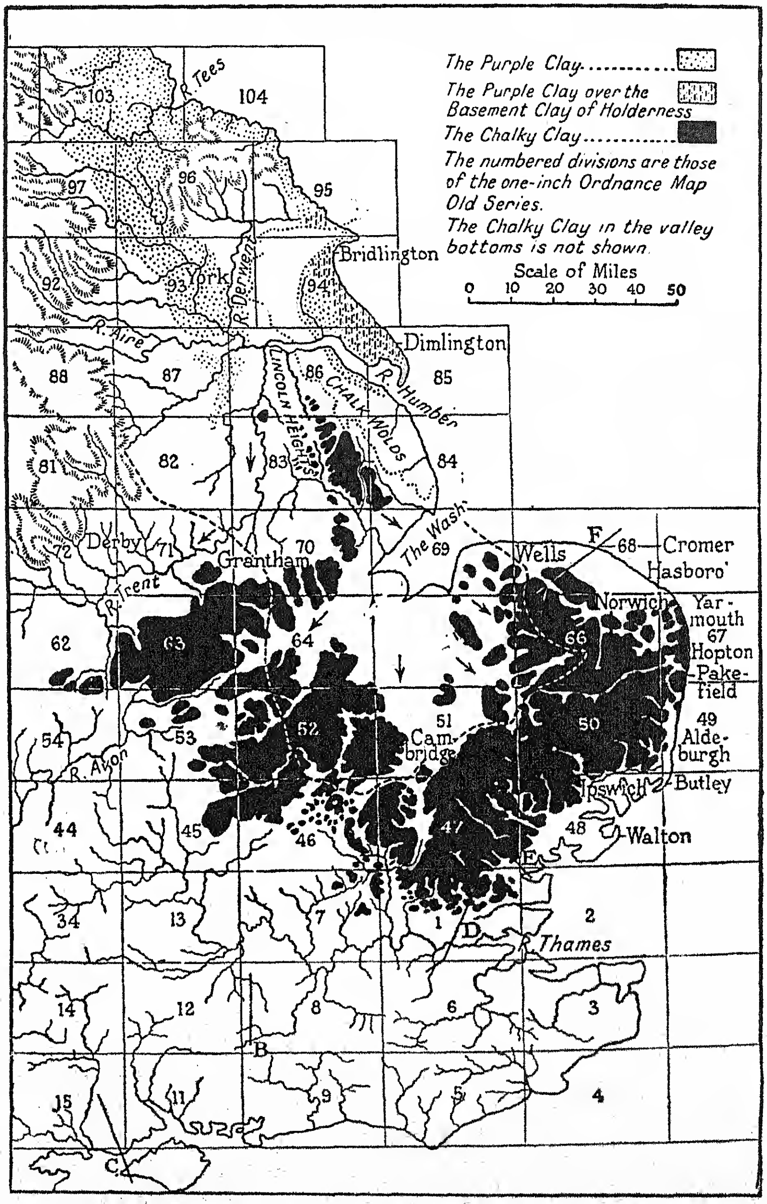


Fig. 128.—Map showing the Distribution of the Purple and Chalky Boulder-clays of the East of England.

The arrows show the suggested direction of flow of the ice.

Wolds. Along the coast, from Flamborough Head southwards, the succession is clearer. At Sewerby there has been found a pre-glacial Chalk cliff, with beach deposits, underlying a basement clay which is correlated with the Little Eastern glacial deposits of Norfolk. Above this comes the Drab Clay, which is equivalent to the Hessle Clay of the Humber basin and to the Hunstanton Clay. At Kelsey near Hull, and at Kirmington in Lincolnshire, are some interglacial deposits which are believed to be of the same age as the middle part of the Drab Clay, while the Purple Clay of Holderness is apparently newer than any boulder clay in East Anglia, but is probably the same as the red boulder clays of the Whitby district and the well-known moraines of the Vale of York, on the northernmost of which stands the city of York. The most striking features of the glaciation of East Yorkshire were the great glacier lakes in the Cleveland Hills and their accompanying overflow channels and river diversions, which have been described in Chapter VI.

The Vale of York and all the western dales leading down to it also show highly developed glacial deposits which cannot be described here in detail. Perhaps the most remarkable effect was the transport of boulders of Shap granite beyond York, as hereafter described. There was also a great glacial lake in the Humber basin.

Even during the maximum advance the greater part of the Cleveland Hills and the moors of north-east Yorkshire remained as a gigantic nunatak, surrounded on all sides by ice-sheets and glacial lakes.

In North Wales the detailed history of the Pleistocene ice-age is not so easy to make out as in other parts of the country, though there appears to be evidence of two advances of ice-sheets with an intervening milder period. But the notable feature is the magnificent display of the characteristic topography of a region of vanished glaciation: indeed it was in North Wales that the former existence of glaciers in this country was first officially recognised.

The main feature of the glaciation of North Wales may be briefly summarised as a struggle between the ice-cap of the native mountains and a vast ice sheet coming down the Irish Sea from the Lake District and Scotland. The power of this last may be judged from the fact that it carried fragments of the bed of the Irish Sea to a height of 1,400 feet in Caernarvonshire; 1,000 feet near Oswestry and 1,200 feet near Macclesfield in Cheshire—while the combined ice-streams carried Welsh and northern rocks in great quantity into Staffordshire and Shropshire and changed the courses of the Dee and even the Severn. Western Caernarvonshire and Anglesey, where the ground is low, were completely overridden and Scottish rocks can be found even in Pembrokeshire.

In the Lake District glacial topography is again admirably displayed and the sequence of events is better known than in North Wales:

moreover, the movements of ice derived from this region can be traced with special clearness owing to the numerous erratics of highly characteristic rocks, especially the granites of Shap and Eskdale and the Ennerdale granophyre. Here again the main characteristic was a fierce and fluctuating struggle between native ice and that from Scot-

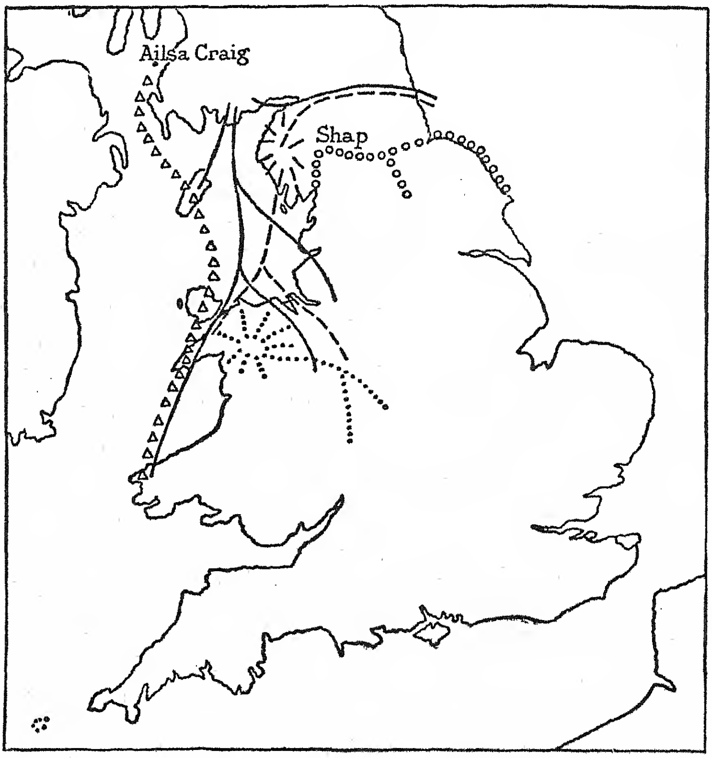


Fig. 129.—Map showing General Direction of Travel of certain characteristic Rocks.

Ailsa Craig rock shown by small triangles, Galloway granites by continuous lines, N. Welsh rocks (especially Arenig volcanics) by dots, Shap granite by small circles, other Lake District rocks by broken lines.

land coming in from the north. The resulting distribution of erratics is discussed on the next page (see also Fig. 129).

There were three periods of advance and retreat of the ice, giving rise in each case to a succession of boulder clay (advance) and sands and gravels (retreat). In the first, the Early Scottish Glaciation, ice coming from Galloway brought boulders of granite from Criffel and other masses: it filled up Edenside and the Solway and drove over into the heads of Tynedale, Weardale, etc. The Main Glaciation was

contemporaneous with the second advance on the east coast, and led to the distribution of Lake District and Pennine ice far and wide, as shown in the map on page 462. The third phase, commonly known as the Scottish Readvance, was a much smaller affair and its effects were mainly confined to the low ground of north Cumberland.

One of the most remarkable features of the Lake District glaciation was the wide distribution in great numbers of boulders of the unmistakable Shap granite, which occupies in situ an area of not much more than a square mile. The boulders are found by the hundred across the Pennines in the Vale of York and on the coast, especially near Robin Hood's Bay. This distribution involves the lifting of an enormous mass of ice over the Pennine range, in which the lowest gap, the Stainmoor Pass, is at about 1,400 feet, and a good deal of the ice actually went over a higher col at about 1,800 feet. This is considerably higher than the outcrop of the granite at Shap, which is moreover on the west side of the deep Eden valley. With this compare the uplift of 1,400 feet at Moel Tryfan in Caernarvonshire (p. 461). The Isle of Man (Snaefell 2,000 feet) was completely overridden by the Irish Sea ice coming from Scotland and the Lake District.

At the maximum of the glaciation the whole of Scotland and most of Ireland were covered by ice, except where some of the highest ground in the north projected as nunataks. The movement of the ice was on the whole radially outwards, in so far as it was not interfered with by the impact of the Scandinavian ice-sheet in the east of England and Scotland. Moreover, local ice-caps in Skye and Mull diverted the west-flowing Highland ice to some extent. Owing to considerations of space it is impossible here to enter into details. The whole thing is admirably set out in W. B. Wright's *Quaternary Ice Age*, Chapters IV–VI, which should be consulted. Careful examination of the literature of the subject shows that there still exists much divergence of views and even positively contradictory evidence as to the relative levels of land and sea at various stages, but one thing seems clear, namely that the Scandinavian ice could not have floated across the North Sea, which is much too shallow to carry the necessary thickness of ice in that way. The motive power of the thrust necessary to drive ice up to 1,000 feet on the seaward face of the Cleveland moors is not easy to explain, if the true gradients and distances are taken into account.

Post-Glacial Deposits

In this category are comprised most of the loose unconsolidated material now forming the actual surface of the land, which should logically include even the cultivated soils. It is obvious that all of these cannot be described here in detail: only the broadest classification can be given, more or less in the form of a list of the more important of the deposits. In point of fact many of them have been dealt with

in earlier chapters, such as raised beaches, submerged forests, river terraces and so on.

On the whole probably the most important class of post-glacial and recent deposits is what may be described generally as alluvium, in the broadest sense: actually this includes most river terraces, as well as great spreads of silt and peat composing the Fenland, though some of this silt is clearly of marine origin. Other very important superficial deposits are the Clay-with-flints and the Coombe Rock and Head of the southern counties, though these are believed to be partly of glacial origin or at any rate formed when the rest of the country was glaciated. Many great spreads of marine gravels also come in here, such as those of Dungeness, as well as the sand dunes and blown sands of many coastal regions. The screes and river gravels of mountainous and hilly regions are also obviously for the most part of post-glacial age and really merge insensibly into alluvium, as in the case of the partly or wholly filled up lakes and tarns of the Lake District and Scotland.

Another important and fairly well-defined category is the cave-deposits, many of which have yielded important relics of extinct animals and early traces of man—chiefly in the form of implements—often buried under stalactitic deposits.

Palaeolithic.—Of late years there has been an enormous amount of research devoted to the investigation of the early stages of human culture in this country and many of the stages thus worked out have been definitely correlated with corresponding phases of the Glacial, Interglacial and post-Glacial periods and deposits. This subject has now attained to the magnitude of a special science, Prehistoric Archaeology, and has become so complicated that it can no longer be included in an elementary textbook of geology. Since, however, some of the earlier stages marked by the use of very primitive implements and tools have been correlated as just mentioned, they may be considered as belonging to geology. This earlier part of the Stone Age, commonly called Palaeolithic, is distinguished by the use of rough stone tools, not polished, as in the succeeding Neolithic age. It is now usually divided into three stages, Lower, Middle and Upper Palaeolithic. In the earlier group only stone tools are found: in the second group there are also a few roughly shaped implements of bone, while in the third well-made tools of bone, horn and ivory occur along with stone implements of finer workmanship. The following is a list of the Palaeolithic stages usually accepted, the names being chiefly taken from places in France:

Younger Palaeolithic.	*Older Palaeolithic.*
Magdalenian.	Acheulian.
Solutrian.	Clactonian.
Aurignacian.	Chellian.
Middle Palaeolithic.	Pre-Chellian.
Mousterian.	

The Acheulian stage is to be correlated with the Great Eastern glaciation of Norfolk, the Mousterian with the Little Eastern and the Magdalenian with the Hunstanton and Hessle Boulder Clays. All of them probably correspond to the two later stages of the Alpine glaciation, the Riss and the Würm, though some of the high level drifts of Yorkshire and the Midlands may be of Mindel age.

It is believed that during the Palaeolithic Age the British Isles were connected with the Continent. It is not easy otherwise to understand how the Neolithic fauna was introduced.

Neolithic.—Remains of Neolithic age are found in many caves, and in artificial excavations in the Chalk which appear to have served as dwellings. They occur also in alluvial deposits at no great height above the present rivers, in peat-mosses such as those of Ireland and the Fenland, and not unfrequently in superficial soil. Many barrows or tumuli have proved to be the tombs of Neolithic man. Often they contain several human skeletons as well as stone weapons, fragments of pottery, and other manufactured articles.

The fauna was decidedly different from that of the Palaeolithic period. Most of the large mammalia had become extinct. But still there remained the elk, the reindeer, the bear, the urus and other forms which no longer live in England. With a few exceptions, however, the fauna was similar to that of Northern and Central Europe at the dawn of history.

Presumably, therefore, the climate was nearly the same as it is at present. Moreover, the general configuration of the land has altered little. The rivers have cut a few feet deeper; in some places the sea has encroached upon the land, in others the land has gained upon the sea. But the changes are insignificant, and geologically the Neolithic age may be looked upon as the beginning of the present period.

CHAPTER XXVII

THE GEOLOGICAL HISTORY OF THE BRITISH ISLES

One of the most striking results of modern geological work on stratigraphy and tectonics has been the realisation of the fact that in certain regions of the earth there has been frequent alternation of periods of quiescence and intense activity. North-western Europe is one of those regions. Hence the geological history of the British Isles can be split up into periods of diastrophism or mountain building, on the one hand, and quiet sedimentation, mainly in the sea, on the other. The periods of diastrophism have usually expressed themselves by the prevalence of continental conditions, with formation of red sediments of the arid facies, such as the Torridonian and the Old and New Red Sandstones, whereas in the intervening marine periods were formed the fossiliferous strata of the Lower Palaeozoic, the Lower Carboniferous and the later Mesozoic. The Tertiary in the British Isles was mainly a continental period, such marine deposits as there were being essentially of very shallow water type, such as are characteristic of a shelf-sea. The dominant feature, therefore, of British geological history has been the extraordinary variability of conditions, as contrasted with the ancient stable land-blocks and the great ocean basins. From this point of view it is very fortunate that stratigraphical geology began in England, since it was there possible to establish definite milestones on the road of time, which have served as a standard for the rest of the world. It must be understood, however, that these periods were not universally of the same character: that is to say that when conditions were quiet in one region, activity prevailed in another, and vice versa. No one geological condition ever extended over the whole earth. It follows, therefore, that the geological history of one region is by no means applicable to another and each has to be treated on its own merits, and one of the greatest problems of geology has been and still is, the reconciliation of the stratigraphical phenomena of widely separated areas of the earth's crust.

So far as is known, the oldest rocks in the British Isles are the Lewisian gneisses and schists of North-west Scotland. They were obviously intensely altered by earth-pressures and metamorphism before the deposition of the next succeeding system, the Torridonian, which in its type area is not metamorphic. But there is nothing to show how many periods of diastrophism and revolution intervened. In Anglesey, as is set forth in the chapter on the Precambrian rocks,

there is clear evidence of two such periods before the beginning of the Palaeozoic, while in other parts of the world there is proof of several between the oldest gneissose rocks and the latest Precambrians of Algonkian type. One of the major problems of British geology at the present time is the question of how many such periods may be represented by the Moines and Dalradians of the northern and central Highlands. This question cannot yet be answered definitely. But the probability is that the apparent simplicity of the Lewisian-Torridonian succession is deceptive, and that a series of events, such as has been clearly made out in Canada and South Africa, has here left no definite traces. Some day, and perhaps before very long, the solution may be provided by one of the methods of age-determination of rocks very briefly alluded to in Chapter XIV, p. 298, but the time is not yet.

The **First Continental Period.**—Whatever the earlier history may have been it is clear that the Torridonian system was formed under continental conditions. Before its strata were deposited, the rocks that covered the Lewisian gneiss were removed and the gneiss itself was exposed to the action of the atmosphere; for the surface on which the Torridon Sandstone rests is rugged and irregular, and had evidently been carved into hills and valleys by rivers and other subaerial agencies. The sandstone itself is a subaerial deposit; and therefore it is clear that during the Torridonian period, and for some time previously, the north-west of Scotland was land. Similar evidence in Norway shows that the land extended into Scandinavia, and probably a continent occupied the north-western part of Europe.

The limits of the continent are not known. It is uncertain whether the Precambrian volcanic rocks of Wales and the Midlands were laid down upon its surface or in a sea that washed its southern shores, but there is no doubt that the red rocks of the western Longmynd were part of the same story; hence at one time the Torridonian continent must have extended thus far to the south.

First Marine Period.—At the beginning of Cambrian times the continent was invaded by the sea in two separate areas; one of these was the great Palaeozoic geosyncline, so often mentioned in Chapters XVI to XVIII, the other was a marine basin, mainly American, which just touched the north-west of Scotland. At the beginning the deposits in the two areas were more or less similar, but in the middle Cambrian they diverged widely, with totally different faunas. After the beginning of the Ordovician nothing is known in Britain of the later history of the northern basin. In the central geosyncline, however, sedimentation was continuous with but trifling breaks for an enormous time, till something like 35,000 feet of marine strata had been piled up. But towards the end of the Silurian red deposits appeared in the upper part of the Downtonian, as the herald of the continental conditions of the Old Red Sandstone. Nevertheless, south of a line more or less

in the present position of the Bristol Channel marine conditions continued.

Second Continental Period.—While the strata of the Old Red Sandstone were being accumulated another period of mountain-building, the Caledonian revolution, was developed in the northern part of Britain and in Scandinavia. The great fold-system then formed had the same strike as the Lower Palaeozoic geosyncline, namely N.E.–S.W., and this determined the dominant trend lines of the whole northern part of the British Isles, as far south as South Wales. At the same time intense igneous activity, both extrusive and intrusive, prevailed in Scotland and northern England. (For further details of this see the next chapter.) This orogenic episode ended before the deposition of the Upper Old Red Sandstone, which in places rests undisturbed on the Highland Schists. There is little evidence as to what was going on in eastern and southern England at this time, except in Devon and Cornwall, where marine conditions continued, but rocks of Old Red Sandstone facies have been met with in deep bores around London. The absence of the Middle Old Red Sandstone in Wales indicates a climax of uplift and denudation at that time, while in northern England deposits of Old Red Sandstone age are at the best very limited if indeed any exist at all. The maximum of the continental type of sedimentation was reached in central Scotland.

Second Marine Period.—It will be apparent from the last section that in the extreme south-west of England marine conditions were continuous from the beginning of the Lower Palaeozoic up till the end of the Devonian, that is to say throughout the second continental period of the rest of Great Britain. But at the end of Devonian times the sea overflowed a considerable part of England, Ireland and southern Scotland, although there was still a large area of land in Wales and the western Midlands. Consequently so far as most of the country is concerned the Lower Carboniferous must be regarded as a marine period, as set forth in the chapter on the Carboniferous system. But this did not last long; even in central Scotland coal formation had then begun, and by the middle of Carboniferous times the whole of England had become an area of deltas and fresh-water swamps, probably something like the modern Amazon valley, with a tropical climate and most luxuriant vegetation, and a constant oscillation of the relative levels of land and sea, mainly however a depression of the land, so that coal measures accumulated to a thickness of many thousands of feet. But towards the end of the Carboniferous period this tendency was reversed and the highest beds of the system are again of the red arid continental facies.

Third Continental Period.—Then rather suddenly there began in north-western Europe another great period of diastrophism, mountain-building and igneous activity, the Hercynian Revolution, with its

double system of Armorican and Variscan mountain chains. The result of this was that all southern Britain, south of a line which may be taken roughly as London–Bristol–Pembrokeshire–Cork was thrown into violent folds with an E.–W. strike and many overthrusts. At the same time in northern England the N.–S. Pennine axis arose with results on the distribution of coal basins that have been described in Chapter XX. This again expressed itself as a violent unconformity between the Carboniferous and New Red Sandstone systems with a concomitant uplift that led to the wide prevalence of arid continental conditions all over England, with all the characteristics of the great desert areas of the modern world.

An important feature of the Armorican revolution was the development of great igneous activity in Devon and Cornwall, with intrusion of great masses of granite, as described in the next chapter. (For a short account of the ore-deposits then formed see also Chapter XIII.) This took place later than the formation of the highest Carboniferous strata, but before the beginning of New Red Sandstone times.

Third Marine Period.—The continental conditions of the New Red Sandstone appear to have come to an end rather suddenly, as shown by the abrupt change of facies between the Keuper and the Rhaetic and the remarkably uniform character of the last named over the whole length of its outcrop from Devon to Yorkshire. Unlike most marine strata immediately succeeding land conditions it does not appear to be diachronic. The British Rhaetic in all essential characters, except the absence of ammonites, belongs to the Jurassic.

Although by far the greater part of the Jurassic and Cretaceous systems consists of marine deposits, they were all formed in a fairly shallow sea of the shelf type with rapid alternations of depth and occasional land areas with deltaic deposits, such as the Middle Jurassic of Yorkshire and the Wealden of southern England. It is not known whether the Mesozoic sea covered the high ground of northern England and Scotland. The numerous variations of facies and local discontinuities were due to the rather mild earth-movements of the Saxonian episode, which are more clearly traced on the continent. It is highly probable that during the Upper Cretaceous arid conditions prevailed over the neighbouring land areas. In the Mediterranean region there was another sea, of different character, often called Tethys. This was separated from the Chalk Sea by a barrier over central France.

This marine period ended rather vaguely in an uplift which put an end to the clear Chalk Sea. This was replaced by muddy water, apparently near the shores of a land with a great river coming from the west over southern England during the early Tertiary. As to what happened in the north little or nothing is known.

Fourth Continental Period.—The events of Tertiary time were mostly due to a far off echo of the great Alpine orogeny of central and southern

Europe. Most of Britain became land and only in the south was there a shallow sea in which the Eocene and Oligocene beds were formed. The principal tectonic episode was the uprise of the anticlines of the Weald and the Isle of Wight, along lines marked out long before by the post-Carboniferous Armorican folds, while in the north-west there was intense igneous activity (see next chapter). During the middle Tertiary the British Isles took on very much their present form, although the Straits of Dover and probably the Irish Sea did not yet exist. The modern drainage system as a whole dates from the Miocene uplift, and the only other later event of first class importance was the Great Ice Age.

A review of the foregoing sections shows that on the whole in Britain continental, or at any rate more or less terrestrial conditions, predominated. In the north once only, in the Lower Palaeozoic, was there long continued marine sedimentation in a geosyncline, while in the extreme south-west of England this persisted till the middle of the Carboniferous. In later periods the marine conditions were at the best those of a shelf sea with frequent local uplifts and interruptions. This result is perhaps somewhat surprising in view of the predominance of marine palaeontology in British geological literature; but the study of unfossiliferous sediments gives much less scope for the invention of new names and alteration of old ones, which appears to be the chief objective of museum palaeontologists, and is therefore officially regarded as of little importance. It is devoutly to be wished that some day British geology may extricate itself from the bog of pedantic nomenclature in which it is at present involved, but there is as yet little sign of so desirable a consummation.

CHAPTER XXVIII

THE HISTORY OF IGNEOUS ACTIVITY IN THE BRITISH ISLES

In the preceding chapter it has been shown that the geological history of the British Isles can be divided up into an alternation of continental and marine periods, and that the succession and duration of these periods are determined by the distribution in time of the major disturbances of the earth's crust. Now it is one of the fundamental principles of modern geology that igneous activity is closely dependent on earth movement. Consequently it follows that the periods of uplift and erosion are in the main also the periods of eruption and intrusion of igneous rocks. As will be seen later, there was one important exception to this, in the Ordovician, but in the other cases the rule holds good.

In the case of the greater periods of igneous activity the sequence of events is in general as follows: (1) eruption of lavas and ashes from vents or fissures; (2) intrusion of plutonic masses in depth; (3) the phase of minor intrusions, dykes, and sills. This order is exemplified by most of the British occurrences, though in some instances the evidences of the volcanic phase have been removed by denudation, while the intrusions remain.

If we consider the igneous history of the British Isles as a whole, we find five great periods of activity, of varying duration. In the case of four of these the maximum coincides with the four chief periods of folding and uplift, while one is anomalous, and occurs in the middle of the first marine period. The table on p. 473 shows the relations of the different geological systems to the periods of folding and eruptivity. It is by no means certain, however, that the Precambrian in Britain included only one major period of igneous activity, and by comparison with other countries this is unlikely. In the absence of fossils in Precambrian rocks it is impossible to ascertain whether the succession in any given area is complete, and it is also usually impossible to be sure whether similar rocks in isolated areas are contemporaneous.

Precambrian.—The Lewisian gneisses of the north-west Highlands, and their probable equivalents in other parts of the country, consist of an enormous but unknown thickness of igneous rocks undoubtedly formed at a great depth, since they are plutonic in character, with later dyke intrusions: the presence of lava pebbles in the Torridon Sandstone shows that a volcanic phase once existed, but the products of it have

been removed by denudation. The plutonic rocks show a wide variety of composition, ranging from granite, through diorite and gabbro to ultrabasic: these form an example of a calc-alkaline plutonic complex on a large scale. After intrusion they were strongly compressed by folding with a N.W.–S.E. strike and invaded by innumerable basic dykes striking with the folds. All this was pre-Torridonian, and the time-interval represented by the Lewisian-Torridonian unconformity may have been enormous. Some of the gneissose 'older granites' of the Highlands are probably also of Lewisian age.

Gneissose plutonic rocks very similar to the Lewisians are also known in Anglesey, at the Wrekin in Shropshire, in the Malvern Hills and at the Lizard in Cornwall. The first three are undoubtedly Precambrian and consist mainly of granitic and dioritic gneisses. The rocks of the Lizard are mainly basic, consisting of gabbro and serpentine, with hornblende-schists and a comparatively small proportion of granite. The Precambrian age of these rocks cannot be demonstrated with certainty. In North Wales (Caernarvon and Llanberis), South Wales (St. David's), and in the Midlands, on both sides of the Longmynd in Shropshire, in the Malvern Hills, at Nuneaton and in Charnwood Forest, Leicestershire, we find a development of the volcanic phase of Precambrian eruptivity, chiefly in the form of acid and intermediate lavas and ashes, rhyolites, devitrified obsidian, and andesites, all much altered. The augite-granophyres of Leicestershire are intrusive into the Charnian rocks and are therefore later. The relation of the volcanic rocks to the Precambrian sediments and to the Lewisians is still obscure, but they are certainly later than the last-named.

Ordovician.—As before stated this phase of igneous activity is anomalous, in that it occurs in the middle of a marine period in a geosyncline. Consequently its products are closely associated with marine strata and many of the eruptions were undoubtedly submarine. Intrusions are scarce and unimportant.

In North Wales the intermediate and basic pyroclastic rocks of Rhobell Fawr come near the base of the Arenig, the acid flows and ashes of Cader Idris just above the basement beds; rhyolites, andesites and tuffs are found at the base of the Arenig, south-west of Carmarthen, at Strumble Head, Trefgarn and Skomer island. The Ballantrae volcanic series of southern Scotland is also of Arenig age. In the Llanvirn of Wales, ashes, rhyolites and andesites are found in several places, Arenig; Cader Idris (pillow lavas); west Pembroke; and at Shelve in Shropshire. But the most important volcanic rocks of this age are the Borrowdale lavas and ashes of the Lake District, comprising at least 10,000 feet of intermediate, basic and acid lavas and ashes, and probably some small intrusions. It is remarkable that the centres of these vast eruptions have not been located. In the Lower Bala come the great masses of lava and ash, mainly rhyolites, of Snowdonia: here the posi-

tions of many of the vents are indicated by great plugs and necks of more or less circular form. The Stockdale rhyolites of the eastern part of the Lake District also belong to this stage. From the foregoing

	Character.	Name of Fold System.	Strike of Folds.	
Tertiary .	4th continental	Alpine	E.–W.	Plateau basalts of Skye, Mull, Antrim. Plutonics of Cuillins, Rum, Mull, Arran, Mourne Mts.
Cretaceous Jurassic	3rd marine	—	—	—
Trias . . Permian . Upper Carb.	3rd continental	Armorican-Pennine	E.–W. N.–S.	Exeter Lavas. Granites of Devon and Cornwall. Whin Sill. Derbyshire toadstones and dolerites.
Lower Carb.	2nd marine	—	—	Basalts of Central Scotland.
Upper O.R.S. Lower O.R.S.	2nd continental	Caledonian	N.E.–S.W.	Lavas of Glencoe, Ochils and Sidlaws, Cheviots. Newer Granites of Highlands, Galloway, Lake District, Donegal, Down, Leinster.
Silurian . Ordovician Cambrian .	1st marine	—	—	Lavas of Wales, Lake District, Salop, S. Scotland. Intrusion of plugs of N. Wales. Assynt complex.
Torridonian	1st continental	—	—	Volcanics of Wales and Midlands.
Lewisian .	Unknown	Huronian	N.W.–S.E.	Plutonic complex of Lewisian Gneiss. Malvern. Older granites of Highlands, Lizard, Anglesey.

account it is clear that volcanic activity occurred in many widely separated localities and at many different dates within the Ordovician; it was a notable feature of the period and was obviously associated with frequent movements within the geosyncline.

In the Assynt district of north-west Scotland, near the line of the

Moine Thrust, is a plutonic complex that has been sheared by the thrust, but is intrusive into the Cambrian and Ordovician dolomitic limestones of the Durness series: it is therefore of later Ordovician or Silurian age. These rocks are unique in Britain, as they are of strongly marked alkaline character, including quartz-syenite, syenite, nepheline-syenite and peculiar types known as borolanite and ledmorite, after the names of localities where they occur. Although of totally different age they show a marked resemblance to the Permian intrusions of Oslo.

The Caledonian Igneous Rocks.—The great Caledonian system of folding, of so much importance in determining the structure of Scotland, Northern England, Wales, and Ireland, began towards the end of Silurian times, reached its climax in the Old Red Sandstone, and in Scotland, at any rate, its igneous effects continued into the Carboniferous and probably even locally to the Permian. Almost everywhere the folding was accompanied by eruption and intrusion of igneous rocks. In Scotland the earliest phase was the intrusion in many parts of the Highlands of a great series of plutonic rocks, known collectively as the 'Younger Granites.' This is a somewhat unfortunate term, since both in Western Scotland and in Ireland there are still younger granites, of Tertiary date, as described later. In the Highlands three principal groups may be recognised, as follows: (1) Caithness and Sutherland; these range from acid to ultrabasic, but hornblende-granites are dominant, such as those of the Ord of Caithness, Beinn Laoghal, and Lairg. (2) Aberdeen and the Cairngorm Mountains: these include some very large masses of muscovite-biotite-granite and biotite-granite at Peterhead, Aberdeen, Lochnagar, and Cairngorm, with smaller masses of quartz-diorite, diorite, gabbro, norite, and troctolite; these basic types are best seen at Ellon and Belhelvie, Aberdeenshire. Small masses of granite and quartz-diorite are scattered about the counties of Banff, Nairn, and north-eastern Inverness. (3) The Western Highlands; here the dominant types are biotite-granite, hornblende-granite and tonalite, as in the great bosses of the Moor of Rannoch, Loch Etive, Ballachulish, and Ben Nevis; the kentallenite (olivine-monzonite) of Kentallen, near Ballachulish, is a rare type. The red granite of the Ross of Mull probably belongs here.

In the extreme south-west of Scotland, in Galloway, three large bosses of granite, at Criffell, Loch Doon and the Cairnsmuir of Fleet, and some smaller ones are intrusive into Silurian sediments: they range in composition from muscovite-granite to hornblende-granite and tonalite: there are also innumerable dykes. In the Cheviot Hills, chiefly on the English side of the Border, is a large mass of lavas, mainly andesites, with a central laccolith of granophyre. In places this shows a marginal augite-granite modification, due to assimilation of the lavas. There are also many radial dykes of felsite and porphyrite.

In the Lake District there are three principal granite masses of this

age, those of Shap, Skiddaw and Eskdale; also the granophyre of Buttermere and Ennerdale and the great gabbro-granophyre complex of Carrock Fell. This last is slightly earlier than the Skiddaw granite, which in its turn has sealed up the cleavage of the Skiddaw Slates, and is therefore later than the main Caledonian orogeny. The Shap granite, an oval mass about one and a half miles by one mile in area is intrusive into Silurian sediments, while pebbles of it are found in the basal conglomerates of the Carboniferous: it is therefore of Devonian (Old Red Sandstone) age. The Ennerdale granophyre with its basic marginal modifications, forms a great stock with nearly vertical walls covering many miles of country, while the Eskdale intrusion, a coarse-grained muscovite-biotite-granite, is larger still. Both of the last-named were accompanied by innumerable dykes. There are also many smaller intrusions of widely varying form and composition too numerous to mention here. The Skiddaw granite is notable for the great size of its aureole of metamorphism, indicating a wide extension of the intrusion at shallow depths, although the actual exposures are small. It is intrusive along the axis of an anticline and it is noteworthy that the strike of this, if continued, passes close to the very similar granites of the Isle of Man and Leinster: these are possibly all connected underground.

Most of the igneous rocks of north-eastern Ireland are Tertiary, but the granite of Newry is Caledonian and very similar to the Galloway granites. In Donegal, Sligo, Mayo and Galway are several large masses of granite, some of which are probably Caledonian, though some may be comparable with the older granites of Scotland. The Leinster granite, before mentioned, is an immense bathylith, 70 miles long on the surface.

The copper-lead-zinc veins of the Lead Hills in Southern Scotland, of the Lake District, of Shropshire, and of North and Central Wales, which lie in Ordovician and Silurian rocks, seem to belong to this age. There is also a little gold in veins around Dolgelly.

Turning now to the extrusive rocks of the Caledonian series, we find andesitic lavas in the Glencoe district in Argyllshire, and a very large development of Old Red Sandstone lavas in the Ochil and Sidlaw Hills in Perth and Forfar, in the district south-west of Edinburgh, and in the Cheviot Hills. These are mostly andesites, and are accompanied by numerous small intrusions of quartz-porphyry and porphyrite. In Scotland volcanic activity remained in full swing into the Lower Carboniferous, giving rise to great outpourings of basalt as plateau eruptions in the central valley, especially in Stirling, Dumbarton, Renfrew, and Lanark, and in Haddington (Garlton plateau). The latest stages were marked by many small volcanoes of the puy type, yielding basalt and even ultrabasic lavas. These form an immense number of necks and plugs scattered about the country accompanied by many dykes,

and in Fife eruptivity seems to have gone on into the Permian. The gradual change from intermediate to basic and ultrabasic lavas is noteworthy. There were also in the Carboniferous some intrusions of distinctly alkaline rocks, including trachyte and teschenite, as necks and sills, as in the Eildon Hills, Traprain Law, Bass Rock, and Car Craig.

The Armorican-Pennine Igneous Rocks.—In this system the axes of the folds run approximately E.–W. in the southern parts of England, Wales, and Ireland, and N.–S. in the north (Pennine anticline). The most important igneous activity manifested itself in Devon and Cornwall, where great masses of muscovite-biotite-granite are intruded into the highly-folded older rocks up to the Carboniferous. There are five chief granite masses at the surface and several smaller ones, all being probably subsidiary domes on the top of a great bathylith. All the masses are very similar, and are characterised by conspicuous pneumatolytic effects, with development of tourmaline and abundant ores of tin, tungsten, copper, arsenic, lead, and zinc, associated with pegmatite, aplite, greisen, and quartz-porphyry dykes (elvans). This is one of the most richly mineralised areas in the world.

In the northern area we find lavas (toadstones) and dolerite intrusions in the Lower Carboniferous rocks in Derbyshire, and further north the Great Whin Sill, an enstatite-dolerite, is intrusive into the Lower Carboniferous over an area of many hundreds of square miles. Connected with the igneous activity, doubtless, is the extensive occurrence of ores of lead and zinc, with fluorspar and barytes, in Flint and Denbigh, Derbyshire, West Yorkshire, Westmorland, Cumberland, Durham, and Northumberland, the ores lying in the Carboniferous limestone.

It was at one time suggested that a group of basalt masses in the western Midlands, at the Clee Hills, Wenlock, Rowley Regis, etc., might be Tertiary, but some of them are now known to be extrusive flows of Carboniferous age, while in two cases age-determinations by the helium method indicate Upper Carboniferous date. Some of these, e.g. the Clee analcime-basalt, are definitely alkaline.

It should be noted that the Armorican vulcanicity of England partly overlapped in time the Caledonian vulcanicity in Scotland: though contemporaneous, these two phenomena were due to different sets of movements, and affected different areas.

The Tertiary Igneous Rocks.—The important and interesting eruptions and intrusions that took place in north-western Britain and north-eastern Ireland in Eocene times must be regarded as a sort of far-off echo of the tectonic disturbances that shook Southern Europe and gave rise to the great Alpine mountain system, but the accompanying movements were for the most part of quite a different character, being mainly normal faulting and block-subsidence, with occasional local folding of simple type accompanying explosive outbursts. The chief areas where igneous rocks of this age are now found are in Skye,

Rum, and some neighbouring smaller islands, Mull, Ardnamurchan, and Arran, with Antrim and county Down in Ireland.

Intensive work by the Geological Survey of Scotland since the beginning of the present century has shown that the whole story is even more complicated than had hitherto been believed, a most important point being that, as before stated, it is now more than doubtful whether fissure eruptions in the strict sense played any part, at any rate in Scotland. Ireland has not been so fully investigated, but as the structures are so similar, the same probably applies.

In most areas, following local small scale explosive eruptions, the first phase consisted in the outpouring of vast masses of basalt forming great shield-volcanoes like those of Hawaii; these are the plateau basalts, formerly thought to be due to fissure eruptions. In Mull these basalts are still 6,000 feet thick in spite of denudation. In all cases this phase was accompanied by formation of explosive vents, one crater in Mull being 6 miles in diameter, with intrusion of great plutonic masses, ring-dykes and cone-sheets. In some instances the centre of activity shifted two or three miles, making the whole thing incredibly complex, as each centre had its own set of intrusions, cutting the older sets. Another very striking feature is the sills and the dyke-swarms; thousands of basic dykes arranged in groups, radiating from the volcanic centres, and striking more or less N.W.–S.E. These extend for many miles, the largest of all, the Cleveland dyke, starting from Mull and just failing to reach the Yorkshire coast near Whitby. In places it is 80 feet wide, and is the biggest dyke in the British Isles.

The igneous geology of south-eastern Skye has already been described in some detail, and this may be taken as a type of the general succession, although Mull and Ardnamurchan are even more complicated owing to the shifting of centres and the abundance of ring-dykes and cone-sheets. In the Isle of Rum is one of the largest developments of ultrabasic plutonic rocks in the world. The Sgurr of Eigg has given rise to much controversy and its true nature can hardly yet be regarded as established. In Arran the chief centre has been deeply denuded and the plateau basalts removed, but in the north of the island the Goatfell granite forms a circular plug 8 miles in diameter, while further south is a deeply denuded ring-complex, very similar to those of Mull and Ardnamurchan. The island of St. Kilda appears to be the remains of another igneous centre, as it consists largely of gabbro and granophyre. The trend of the very numerous dykes crossing Jura and Islay suggests another plutonic centre under the sea to the N.W. of Islay, but it is unlikely that plateau basalts ever extended over these islands, where Precambrian rocks rise to a height of over 2,500 feet. The view that all these scattered occurrences once formed part of a vast continuous lava-plateau, extending up to the Färoer and Iceland, now seems very improbable.

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